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PREFACE

This is the tenth volume of the series. It is with feelings of both surprise and gratification that this Preface is prepared; surprise at the rapid passage of years, and gratification that this venture has found wide acceptance. The Editor is much indebted to the many able investigators who have been willing readily to prepare authoritative reviews of their fields of interest. Such reviews do indeed advance the whole profession. Ninety topics have been dealt with in the ten volumes, with little repetition or overlapping. From time to time it is anticipated that there will be deliberate return to some of the topics treated earlier in order to bring to the reader an account and evaluation of recent activities. To a degree the chapter by Nelson and Stanford is of this nature and supplements the information on fertilizers and fertilizer practices presented by Jones and Rogers in Volume I.

Perhaps it is also appropriate to repeat that in selecting topics for review, and in discussing with authors the scope of their contributions, the interactions and interdependence of crops and soils are always stressed. In the Preface to Volume I it was further stated that "the editors' definition of what constitutes agronomy is catholic; they will be guided in their choice more by what information may be of use to agronomists than by what constitutes agronomy." An example might well be the fascinating account by Stakman and Rodenhiser of the appearance and spread of race 15B of wheat stem rust.

In this issue also there is continued the policy of including material dealing with regional agriculture. There are few areas that present a greater diversity of agronomic problems than the Great Plains. Olson and his colleagues have discussed these comprehensively.

Another feature of this series has been the inclusion from time to time of longer articles in the general field of soil classification and morphology. Stephens and Donald have prepared an account of the soils of Australia and have gone further than the authors of some other papers of this type by discussing crop responses to major and minor fertilizer elements which have been spectacular because of the unique character of certain deficiencies therein.

Ann Arbor, Michigan A. G. NORMAN
November, 1958

CONTENTS

AGRONOMIC TRENDS AND PROBLEMS IN THE GREAT PLAINS

COORDINATED BY R. V. OLSON

CHANGING CONCEPTS OF PLANT NUTRIENT BEHAVIOR AND FERTILIZER USE

BY WERNER L. NELSON AND GEORGE STANFORD

RACE 15B OF WHEAT STEM RUST—WHAT IT IS AND WHAT IT MEANS

BY E. C. STAKMAN AND H. A. RODENHISER

AUSTRALIAN SOILS AND THEIR RESPONSES TO FERTILIZERS

BY C. G STEPHENS AND C. M. DONALD

CASTORBEANS: A NEW OIL CROP FOR MECHANIZED PRODUCTION

BY LEROY H. ZIMMERMAN

SAFFLOWER

BY P. F. KNOWLES

REACTIONS OF AMMONIA IN SOILS

By M. M. Mortland

NEW GRASSES AND LEGUMES FOR SOIL AND WATER CONSERVATION

By A. L. Hafenrichter

THE ROLE OF SULFUR IN SOIL FERTILITY

By Howard V. Jordan and L. E. Ensminger

CORN PLANT POPULATION IN RELATION TO SOIL PRODUCTIVITY

BY G. H. DUNGAN, A. L. LANG, AND J. W. PENDLETON

LIMING

BY N. T. COLEMAN, E. J. KAMPRATH, AND S. B. WEED

AGRONOMIC TRENDS AND PROBLEMS IN THE GREAT PLAINS

Coordinated by R. V. Olson

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Contents

I. The Great Plains Area

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A. INTRODUCTION

The Great Plains of the United States constitute a large segment of nearly level to gently rolling land interspersed with some rough drainageways and some sand dunes. The area extends through the center of the nation from the Canadian border to southern Texas. It is bounded on the west by the Rocky Mountain watershed divide and includes a large portion of ten states. The exact eastern boundary of the Great Plains is not well defined and has been delineated in various ways. In general, this boundary approximately corresponds to the zone separating the true prairie, dominated by tall and mid grasses, from the mixed prairie of short and mid grasses, and separating soils which have a zone of lime accumulation from those which do not. The area currently recognized by the U.S. Department of Agriculture[1] to be the Great Plains area is indicated in Fig. 1. It is this area to which the discussions in this chapter pertain.

The Great Plains area provides a tremendous force in American agriculture. The ten states in which the Great Plains lie contain about 37 per cent of the nation's land area and 40 per cent of its cropland. Normally these states produce about 60 per cent of our wheat and 35 per cent of our cattle.

Since its settlement by adventurous easterners, for the most part less than one-hundred years ago, the Great Plains area has been confronted with many agricultural and economic problems. These problems have stemmed primarily from periods of drought, intense winds, low prices, and overproduction, interspersed with periods of favorable climate, high prices, and national or international food shortages. As a result of these factors there have been many fluctuations in farm income, land use, land tenure, land prices, rural and urban population, and general economic well being.

During periods of favorable weather conditions there has been a tendency for new land to be plowed from its native grass. Throckmorton (1955) has estimated that almost nine million acres of grassland and other

[1] *U.S. Dept. Agr. Misc. Publ.* **709**, 1956.

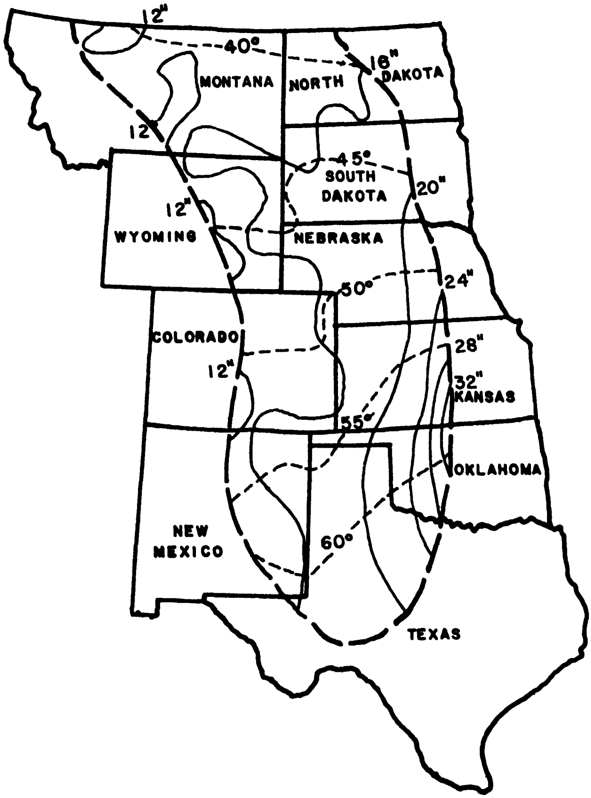

FIG. 1. The Great Plains area with normal annual precipitation in inches (1921–1950) and average annual temperatures (°F., 1899–1938).

stabilized land were broken for cultivation in the Great Plains during the period 1944 through 1955. Almost an equal acreage of land was returned to grass during this period. The estimates show a direct relationship between weather conditions and changes in grassland acreages. For instance, in 1948, a favorable year, over twice as much land was broken as was revegetated. In 1955, a drought year, only about 300,000 acres were broken while about 650,000 were revegetated either by reseeding or by natural revegetation.

During the earlier history of the Great Plains there was an influx of settlers in favorable years. Farmers and investors accustomed to more humid conditions placed a high value on land, which caused high land prices and many non-resident or "suitcase" farmers. In less favorable pe-

riods there was an exodus of people which resulted in land abandonment. The only people who remained were those who had developed stable systems of farm and ranch management or those who were financially unable to move.

For the past twenty years many efforts have been made to stabilize agricultural and economic conditions. Various governmental programs have been established and agricultural research has been intensified. In 1935 the Great Plains Agricultural Council was established, initially involving only the southern Great Plains. This council meets at least once annually and is composed of representatives of all state and national agricultural agencies of the area. The Great Plains Agricultural Council has been responsible for many studies and reports on Great Plains problems and has been instrumental in promoting agricultural adjustments, research, and governmental action programs.

The impact of efforts to stabilize conditions in the Great Plains is beginning to be felt in many ways. The best illustration of this fact lies in the comparative economic and social effects of the droughts of the 1930's and the 1950's. While the latter drought did not affect as large an area as the former, in many areas it was more severe. Yet, partly because of agricultural research and education, and partly, no doubt, because of governmental programs and favorable economic conditions in the nation generally, the effects of the drought of the 1950's have not been nearly as severe as those of the 1930's.

To many, the solution to the problems of the Great Plains has seemed to be to return all the land to grass and to convert fully to a range agriculture. To the wheat farmer, however, who owns a large acreage of level, fertile land capable of producing yields of 40 to 45 bushels per acre in exceptionally favorable years the solution seems quite different. This farmer feels that much of the land in the Great Plains is better suited for wheat production than any other area of the United States and that unlimited production should be permitted in the years that are favorable for crop growth. Undoubtedly many cultivated areas of the Great Plains should be revegetated in the best interests of all concerned. It also seems likely, however, that there is a permanent place for the grain and livestock farmer who is a careful manager and who will build up reserves in good years to carry him over the unfavorable seasons.

The problems mentioned above indicate the great need for agricultural research in the Great Plains area. The challenge is especially great in the field of agronomy since the problems are so closely related to the production of cultivated and range crops. In the later sections of this chapter the authors point out specific agronomic problems and the present status of research on these problems.

B. Climate

The average annual temperature and normal amount of precipitation for the Great Plains area are shown in Fig. 1. It can be seen that temperatures increase steadily from north to south and rainfall decreases from east to west. Of particular significance to agriculture is the fact that rainfall is low throughout the Plains. Thornthwaite (1941) classifies the eastern part of this area as normally having a dry subhumid climatic type and the western portion as being semiarid.

Because of variations in the movement of moist or dry and hot or cold air masses over the region, the Great Plains area is subject to extreme climatic variations. These are even more detrimental to agriculture than the low average rainfall. Tropical air masses, which normally flow northward over the Plains and meet cold air masses, usually come from the dry plateau of Mexico and result in little precipitation. Occasionally, however, moist air from the Gulf of Mexico swerves westward from its usual northeastern path, resulting in heavy precipitation in the Plains. According to Thornthwaite (1941) severe rainstorms anywhere in the Plains may bring as much as a third of the average annual precipitation in a single day or a fifth in a single hour. On the other hand, periods as long as 120 days may occur during which no rain falls. Hailstorms are also common during the summer months. Precipitation throughout the area is greatest in spring and early summer and least in winter.

Extreme variations in annual precipitation occur throughout the area. Palmer (1957) has classified the year-by-year climate for 60 stations in the Great Plains over a forty-year period according to climatic types. Data for five representative locations are shown in Table I. These data illustrate the great variability of climatic conditions. At each location the rainfall surpasses that of a semiarid climate frequently enough to encourage the development of a cultivated agriculture. Ensuing periods of semiarid or arid climate may prove disastrous to agricultural endeavors.

Even a brief discussion of the climate of the Great Plains would not be complete without mentioning wind movements which hasten evapo-transpiration and cause soil erosion. Zingg (1950, 1953) has studied wind records in the central Great Plains. Average wind velocities are considerably greater in the Plains than in the area to the east. In Kansas, for instance, wind velocities are almost twice as great in the western portion of the state as in the eastern portion. In the central Plains the greatest wind velocities usually occur in April, which has an average wind velocity of about 8.5 miles per hour at a 2-foot height. Velocities of 28 miles per hour for a duration of one hour may be expected every two years and velocities of 43 miles per hour for a duration of one hour may be expected

TABLE I

Climatic Variability at Five Locations in the Great Plains[a]

Location	Per cent of years having indicated climatic type				
	Arid	Semi-arid	Dry subhumid	Moist subhumid	Humid
Northeastern Montana	8	67	22	3	0
Central South Dakota	3	51	40	3	3
Northwestern Kansas	5	52	35	8	0
Northwestern Texas	10	53	32	5	0
Central Oklahoma	0	5	30	27	38

[a] Data from Palmer (1957).

every fifty years. The level of atmospheric wind movement tends to be higher during periods of drought than during periods of favorable precipitation.

C. Soils

The eastern edge of the Great Plains region as defined in Fig. 1 closely corresponds in the northern portion to the eastern edge of the Chestnut soils. In the central Plains it follows the boundary between the Prairie (Brunizem) soils and the Chernozem soils. In the South this line follows the eastern edge of the Reddish Chestnut soils. The western portion of the Great Plains region, where lower rainfall conditions exist, has Brown soils occupying most of the area with Reddish Brown soils occurring in Texas and the southern part of New Mexico. All of the zonal soils of the region thus have developed under low rainfall conditions and have a calcium carbonate accumulation zone at some point in the soil profile. In general this zone is formed closer to the surface as the climate becomes drier. In fact, soils in the extreme western portion may have calcareous surface horizons.

In addition to the zonal soils, several azonal and intrazonal soil groups exist throughout the region. Wide belts of alluvial soils occur along the Missouri, Platte, Kansas, and Arkansas River systems. Saline and sodic (alkali) soils, lithosols and dry sands also are present in various sections.

The soils of the Great Plains have developed from a variety of parent materials. Glacial till is present beneath soils in parts of the three northern states of the region. Loess deposits are widespread throughout the Great Plains and provide the parent material for many of the soils. Calcareous clays, lacustrine deposits, aeolian sands, alluvium, clay shales, limestones,

and sandstones form parent materials for soils in various places. Thorp *et al.* (1949) have discussed the parent materials and soils of the northern Great Plains in more detail and North Central Regional Publication 76 (1958) describes the soils in the four Great Plains states in that region.

The desirability of basing land-use adjustments in the Great Plains on soil characteristics has been widely accepted. Lack of adequate soil survey information has hindered this practice. As of January 1, 1957, there were only 18 counties in the Great Plains area with completed recent standard soil surveys. As a step in hastening the completion of soil surveys the U.S. Department of Agriculture in 1956 began accelerating its soil survey activities over the southern half of the Great Plains where the most critical wind erosion conditions existed in 1954 and 1955.

Because of the nearly level to gently rolling topography of the Great Plains much of the region is easily cultivated and well adapted to large-scale farming. Although several large areas of soils with sandy surfaces exist, the greatest portion of the Plains has surface soils of finer textures that are less subject to wind erosion. Soils are generally uniform and large fields may have only one or two soil types present. Data taken from the 1954 Census of Agriculture show that 83.2 per cent of the land of the entire ten states in which the Great Plains are located is in farms. Of the more than 588 million acres in farms 30.8 per cent is cropland, 62.8 per cent is pasture, and 6.4 per cent is woodland. Comparable figures for the Great Plains area only have not been compiled but, if available, would probably show a higher portion of the land as cropland since most areas west of the Plains are either mountainous or have drier climates and are used as range land.

II. Field Crops

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A. Field Crops of the Region

The quest for gold in the sixteenth century brought Coronado into the Southern Great Plains. This "gold" was discovered in the form of the field crops of the Great Plains in the nineteenth and twentieth centuries. It can be mined every year, generally in profitable quantities, and should be available for many years to come, providing adequate soil management is practiced. Economic utilization of farm lands in the Great Plains has continued because of parallel progress in better soil management, improved farm machinery, and use of adapted and improved field crops. Each of

these three subjects is an interesting development as pertaining to modern farming in this region but only a few comments will be made on the latter subject.

All the field crops that have been grown or now are being produced in the Great Plains are plant introductions. Most of the area was originally covered with tall grasses in the east which give place to short grasses in the west. Much of the lands which had soil of reasonable depth and were not too sandy have been turned by the plow. We are aware that too much marginal land has been broken from the native vegetation. However, many of these areas have proved suitable for the production of drought-resistant crops, such as wheat and sorghum. These are grown annually in the more humid area, and alternated with fallow in the drier and marginal areas. They truly are "gold," as exemplified by ripening wheat fields.

Some of these imported crops grown in the Great Plains include cotton, corn, wheat, oats, barley, rye, sorghum (including grain, forage, grass and broomcorn), the millets, alfalfa, sweetclover, field peas and beans, cowpeas, vetch, sugarbeets, potatoes, sunflowers, castorbeans, and safflowers. Wheat is grown throughout the entire region; cotton and sorghum predominate on the Caprock area of Texas in the south, sorghum and wheat in the area immediately north, corn and wheat in the central portion, and wheat and flax are perhaps the more important crops in the north. At one time northwestern Kansas was the largest export center of corn in that state and the nearby areas of northeastern Colorado and southwestern Nebraska were large producing centers. Corn now has found its place largely in central Nebraska, especially under irrigation, and is grown as far north as Montana. Sugarbeets thrive under irrigation in Colorado, Montana, Wyoming, Nebraska, and Kansas. Alfalfa does well throughout the region on both dry land and under irrigation and in years of favorable weather conditions, large quantities of seed are harvested in Oklahoma, Kansas, Nebraska, and the Dakotas.

College text books on field crops (Martin and Leonard, 1949) give more information than adequately can be presented in this discussion. The ten Great Plains states have an abundance of cultivated acres and produce a large volume of cereals, hay, seeds, sugar, and fiber annually. Percentage of United States acreage and production of some of the important field crops of the ten states in which the Great Plains are located are given in Table II. In the ten-year period 1945–1954, over half of the nation's wheat, sorghum, and flax and about one-third or more of the alfalfa seed, cotton, barley and sugarbeets were produced in this region. Acre yields were lower than the United States average as can be observed in comparing the percentage of United States acreage with the percentage of production. In all cases the acreage percentage is higher than production percentage. This

is what might be expected in an area where drought is a continuous production hazard. Large scale farming and modern machinery tend to decrease per acre costs of production. Even seed costs are less. For example, 20 to 30 lb. of wheat are sufficient to plant an acre in some parts of western Kansas whereas in the more humid areas as much as 90 lb. of seed are needed. Detailed changes in important crops by counties is given by Weaver (1954) for North and South Dakota, Nebraska and Kansas.

TABLE II

Acreage and Production of Some Important Field Crops in the Ten Great Plains States in Comparison to Total United States Production, 1945–1954[a]

Crop	Percentage of United States harvested acreage	Production: Percentage of total United States production	Production: Leading Great Plains states nationally
Alfalfa (hay)	33	28	Nebraska 4th
Alfalfa (seed)	68	50	Kansas 2nd, Oklahoma 3rd, Nebraska 4th
Barley	53	43	North Dakota 2nd, South Dakota 4th
Corn	23	16	Nebraska 5th
Cotton	45	31	Texas 1st
Field beans	32	27	Colorado 4th
Flax	66	58	North Dakota 1st, South Dakota 3rd, Texas 5th
Oats	28	23	South Dakota 5th
Sorghum (grain)	96	93	Texas 1st, Kansas 2nd, Oklahoma 3rd, New Mexico 5th
Sorghum (forage)	93	87	Texas 1st, Kansas 2nd, Oklahoma 3rd, Nebraska 4th, Colorado 5th
Sugarbeets	41	37	Colorado 2nd, Nebraska 4th, Montana 5th
Wheat (all)	72	62	Kansas 1st, North Dakota 2nd, Montana 3rd, Nebraska 4th, Oklahoma 5th

[a] Information computed from data obtained in "Agricultural Statistics, 1956." U.S. Dept. Agr., Washington, D.C., 1957.

As many of these cultivated acres are marginal lands, the percentage of abandonment is high. The abandonment of wheat in the region during 1945–1954 averaged 12.3 per cent while for the remaining wheat lands in the United States it was 5.6 per cent. These figures for corn were 2.3 and 1.5 per cent; for barley, 10.8 and 10.2 per cent; and for oats, 13.1 and 5.6 per cent respectively. Abandonment figures for the drier areas of the Great Plains are still higher. For example, in some western Kansas counties

farmers harvested only 6 to 8 acres of wheat for every 10 acres planted during 1916 to 1952.

Many different crops have been grown in this region in the past but the kinds of field crops being produced now (1957) are perhaps fairly well stabilized. Some changes can be expected to occur in small areas where additional irrigation is developed but even under these conditions, cotton, sorghum, corn, sugarbeets, and alfalfa are well established. The prospects of introducing entirely new crops into the region are small with the present information we now have on other cultivated crops.

The two crops that predominate in the Great Plains area, as measured by the percentage of the crop produced in the United States, are sorghum and wheat. Ninety-three per cent of the grain sorghum, 87 per cent of the forage sorghum, and 62 per cent of the wheat grown in the United States was produced in the ten Great Plains states during the period 1945–1954. Both of these crops are adapted for growing in the semi arid region typical of the Great Plains. In the southern part, wheat is grown as a winter crop and in the north as a spring and summer crop, although in Montana winter wheat is now almost as important as spring wheat. Sorghum is a short-day plant and requires high temperatures. The most favorable temperature is about 80° F. with a minimum of 60° F. Therefore this crop is best suited to the southern half of the region.

B. Sorghums

Sorghums followed the earlier settlers into the Great Plains. During the 1870's and 1880's in southwestern Kansas a number of pioneer families existed through the winter months on kafir mush which was the only crop they had produced. Normally we do not use sorghum for food but in Africa, the probable origin of this crop, sorghum is an important food crop. Nearly all of the sorghum grain and forage produced in the Great Plains is utilized for livestock feed and only a small amount goes into industrial uses.

The original home of sorghum was probably a semi-tropical area and the kinds first introduced into the United States were tall and late to mature. The kafirs and milos, however, produced satisfactory grain crops in the southern part of the region but because of late maturity they could not be grown with much success any farther north than Kansas (Fig. 2). The early sorghum varieties were not adapted to machine harvest. Selections made from these originally introduced varieties gave earlier and somewhat shorter types, such as Dwarf Yellow Milo and Western Blackhull. However, it was the development of combine-type grain sorghums, pioneered by John B. Seiglinger of Oklahoma, that made it possible to grow sorghums using wheat machinery. The development of the earlier maturing varieties

extended the area of grain sorghum production north into Nebraska and higher altitudes of Kansas and Colorado (Fig. 2). Such varieties as EARLY KALO, COES, SOONER, COLBY, and DAY were responsible for this expansion. Varieties soon followed, such as MARTIN, MIDLAND, and REDBINE 60, that further established this as an adapted area for grain sorghums. The breed-

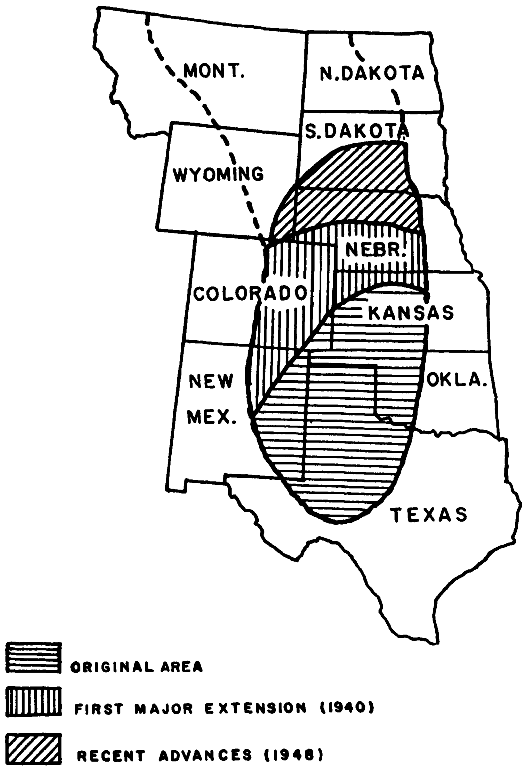

FIG. 2. Northern expansion of the grain sorghum area of adaptation in the Great Plains region due to breeding early maturing varieties.

ing of adapted grain sorghums in South Dakota, particularly NORGHUM and RELIANCE, extended the area of grain sorghum still farther north (Fig. 2). The results of sorghum breeding have extended the area of adaptation of this original semi-tropical plant about 400 miles north.

In its present area of adaptation sorghum furnishes an alternative crop to grow with cotton in the Caprock area of Texas and with wheat in other areas of the Great Plains. Sorghums respond well to irrigation and grow

well on sandy soils where wheat does poorly. During the last thirty years sorghum varieties have been tailor-made to fit large scale modern farming practices and more northern areas (Quinby and Martin, 1954). Production of grain sorghums for 1957 was estimated at 481 million bushels which is nearly double the previous record crop of 1955. Even in the wheat state of Kansas, sorghum exceeded all other cereal crops in grain production in 1957.

Moisture generally is the limiting factor in crop production in the Great Plains. The lack of suitable moisture in the fall of 1956 prevented many acres of winter wheat from being seeded. Rains the following spring made it possible to seed sorghums on fields prepared for wheat, which accounts for a large part of the record grain sorghum crop in 1957. This illustrates how wheat and sorghum can be interchanged readily where these two crops are adapted.

Hybrid sorghums are the latest development in this crop. It is not known whether the area of sorghum adaptation will be extended by hybrids but performance will be improved. During 1957 it was observed that hybrid sorghums developed more rapidly early in the season under cool growing conditions and reached the blooming stage earlier than standard varieties which were thought to be of the same maturity.

C. Wheat

Wheat has been grown for many years in the United States (Salmon *et al.*, 1953) but not until two introduced varieties, MARQUIS hard red spring and TURKEY hard red winter, came into the Great Plains were there suitable varieties for the region. A bulletin published by the Kansas Agricultural Experiment Station in the 1870's stated that wheat probably would not be a successful crop for Kansas. That statement was based on experiments conducted with spring and soft wheats. TURKEY wheat came with the early settlers just as did sorghum. In 1873, a small group of Mennonites emigrated from southern Russia to central Kansas, bringing this variety with them. TURKEY wheat was widely adapted to the southern Great Plains and rapidly replaced the spring wheat varieties and the soft wheat varieties previously available. There is probably no TURKEY wheat as such being grown in the Great Plains area now (1957) but there are direct selections from Turkey, such as NEBRED and CHEYENNE; children such as TENMARQ; and many grandchildren such as PAWNEE, COMANCHE, CONCHO, WESTAR, and WICHITA being grown on farms in the region. YOGO has been selected for increased winter hardiness to extend the winter wheat area farther north in Montana. It also has TURKEY in its pedigree.

FIFE wheats and BLUESTEM and selections of these varieties were grown in the spring wheat area prior to 1900 but not until MARQUIS was intro-

duced from Canada in 1912 was there a satisfactory spring wheat variety for the northern Great Plains. The advantages of MARQUIS were early maturity, high yield, and excellent quality. The early maturity aided in escaping damage from the rusts and also may have accounted for its ability to perform well under drought conditions. Where rust is not a serious annual problem, as in certain areas of Montana, MARQUIS is still being grown. MARQUIS has been used widely as a parent and such varieties as CERES, THATCHER, MIDA, REDMAN, and more recent varieties such as LEE, RESCUE, and SELKIRK all have this variety in their parentage.

MARQUIS and TURKEY wheats should be given credit for the wide-scale production of wheat in the region and for its settlement by farmers. Germplasm of these varieties has been interchanged as many of the hard red winter wheats trace their parentage to TENMARQ which has a selection of TURKEY and MARQUIS for its parents. KANRED, a selection of TURKEY, also occurs in the parentage of THATCHER which in turn has been extensively used in the breeding of hard red spring wheats.

D. Present Problems and Future Possibilities

Moisture will always be a major problem in the Great Plains. Plant breeders cannot produce plants that will grow without water. Under both dry farming and irrigation, field crop production is intimately related to moisture conservation through proper soil management practices. Continued research directed toward the utilization of water is essential.

During the last fifty to one-hundred years of farming in the region, the crops best adapted to local areas have been selected. In spite of the desirability of growing other crops, farmers in some areas depend almost entirely on wheat for field crop production. Present information indicates that there are no other crops that can be substituted successfully for those now being grown in the Great Plains. This does not exclude the possibilities that other crops may be found or developed that will compete with those now grown. Therefore some emphasis should be placed on research designed to develop or find new crops adapted to the region. However, since experience has shown the Great Plains to be well adapted to wheat and sorghum production these crops should receive concentrated research effort. This can be done by breeding better varieties, improving soil management practices, and developing better mechanical processes of production.

There are certain limitations concerned with breeding better field crops for semi-arid regions. The plant breeder's methods are no different than the procedures that occur under natural evolution. Wheat and sorghum were already adapted to drought conditions before man attempted to make improvements. Further progress along this line can be expected

to be slow. It is much easier to change plants with respect to characters such as disease-resistance, maturity, and straw strength than it is to change characters of a complex physiological nature such as drought-resistance, winter-hardiness or, for example, to develop a sorghum that will grow at a minimum of 50° F. instead of 60° F. These present problems should not discourage research along these phases of breeding. However, at the present adequate information is not available to attack the problem of breeding drought-resistant or cold-resistant crops except by actually growing and studying segregating populations under the natural environment.

Scientific research in agriculture for future progress probably will pass through three phases before results can be transferred to the farm. Basic research comes first. This is a slow unspectacular process. Plant studies of a basic nature need immediate attention. Applied research, the second phase, is entirely dependent upon facts obtained from studies of a fundamental or basic nature. In general, most experiment stations and colleges in the Great Plains are well staffed to do this job. They are also equipped to carry out the third phase, which is the bringing of practical results of scientific research to the farm through adult education.

We are fairly certain that winter cereals produce better than spring sown cereals if they can survive the winter. Increased winter hardiness in wheat, rye, barley, and oats should increase their production potential. However, progress in this direction is being made slowly because of the lack of basic research. The future progress in field crop production in the Great Plains primarily will depend on facts obtained through basic research. This will require the close coordination of people in the special fields of plant and soil science. As we continue to become more specialized, it becomes more imperative that we have an adequate overall coordination of these research teams. Whether progress comes from studies related to water use or by better crop varieties is not important. It is evident, however, that basic research in all fields of agricultural research will contribute to maintaining and increasing the agricultural output of the Great Plains.

III. Pasture and Range Crops

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A. Present Situation

1. Range Condition

Southern Texas and the southern Great Plains appear in 1957 to be emerging from the most severe and intense drought on record. For much

of the area the Great Drought of the 1930's was not nearly so severe as the Great Drought of the 1950's. The extreme deficiency in precipitation appeared to move northward as the years advanced. At the present time, parts of South Texas have had seven to eight years of extreme drought, parts of Oklahoma have been below normal for five to six years, parts of Kansas and Colorado for four to five years, and parts of Nebraska have experienced a two- to three-year drought. To the northward, the western portions of the Dakotas and eastern Montana were affected by severe drought in 1956. In general, however, conditions have been favorable in the Northern Plains for a number of years.

Despite the extreme drought to which most of the southern Great Plains have been subjected, a recurrence of the widescale financial distress and sociological upheavals of the 1930's did not take place. There are several reasons for this. The prices offered for agricultural products have been relatively stronger; farming and ranching units have been larger and more efficient; the development of industry and associated enterprises has offered part-time or full-time employment to farmers and ranchers in distress; but perhaps more important, farming practices are far more advanced today than in the 1930's. Due to a large extent to research and extension programs, the modern farmer and rancher is doing a much better job today than he did twenty years ago.

On the other hand, strong prices and a narrow margin of profit on livestock have tended to encourage heavy stocking during a critical drought period. The result has been a very disturbing degradation of range condition throughout the southern Plains. The enormous increase in brush on Texas and Oklahoma rangelands cannot be blamed altogether on either the recent drought or economic pressures. Rather, it is the fruit of a half century or more of chronic overgrazing and mismanagement. The trend toward degradation of range condition was sharply accelerated in the last ten years. Brush encroachment is not universal because woody species do not thrive on some soil types, but in range types where brush does not thrive, the deterioration in range condition has been just as great if not so spectacular. Ragweed, broomweed, broomsedge, triple awn, and similar plants of low value have taken over millions of acres where the better native grasses were once dominant and important.

In the central and northern Great Plains, conditions are generally much better and much of the rangeland is in good and excellent condition. Precipitation has been not only more favorable in the north, but stocking rates have been tempered by the need for winter forage, and the generally lower land values have eased the pressures for maximum per acre production. The northern rangelands have grass enough for expansion of the livestock

industry. The southern rangelands will need to produce additional forage in order to accommodate any significant expansion.

2. Revegetation

Extensive abandonment took place throughout the Great Plains during the 1930's. In the northern Great Plains a very high proportion of the abandoned farm lands was seeded to crested wheatgrass in the late 1930's and early 1940's. Although some of the reseeded land has since degenerated in condition and productivity, the major task of revegetation was essentially completed. In the southern Great Plains abandonment is still continuing and a comparatively small proportion of the acreage has been seeded to permanent grasslands. The reasons for continued abandonment are primarily the greater number of small holdings, the greater erodibility of the soils, the more extensive use of cotton, sorghum, and similar row crops, and the drought of the 1950's. The reasons for relatively little progress in revegetation are primarily the erratic and inadequate supply of adapted seed, the problems encountered in handling, marketing, and testing seeds, and the difficulty of obtaining stands.

There is nothing available in the southern Great Plains comparable to crested wheatgrass as a range plant. Most of the seedings attempted have been with native grasses and the seed supplies have been erratic (Harlan, 1955). The greatest acreages have been seeded to "mixed bluestems," sand lovegrass, blue grama, buffalograss, western wheatgrass, switchgrass, sideoats grama, and indiangrass in approximately that order. Except for sand lovegrass and switchgrass, most of this seed has come from wild harvests (Hoover *et al.*, 1947). Seed is produced on native stands in abundance in some years and very little is produced in other years. There has not been a good mixed bluestem harvest since 1950 and the last really large one was in 1949. Some blue grama is produced each year on the high plains but the source varies from year to year. The different sources give widely different performances. The same situation applies to buffalograss, sideoats grama and to a lesser degree to western wheatgrass. The bulk of the sand lovegrass and switchgrass seed now comes from fields artificially established to these grasses.

Stand establishment generally is more difficult in native grasses than in a grass like crested wheatgrass. The seedlings are slow growing and require protection in their early stages. Drilling into a sorghum stubble or residue has been the most satisfactory method. Seedings on other seedbeds fail much more frequently. Crested wheatgrass not only has more seedling vigor but can be seeded in the fall or very early spring and will germinate and grow at cool temperatures. This gives the grass a decided

competitive advantage over weeds and permits the use of fallow, small grain stubble or even weed-covered seedbeds.

Most of the native grass seeds are chaffy and difficult to handle. Routine analyses required for interstate shipment or for seed trade channels are very difficult and expensive to conduct (Harlan, 1957). Laboratory time required to run a single purity test on a lot of chaffy seed is frequently in excess of 12 hours and the charges are correspondingly high. Even with the time and attention required for such an analysis the results often are not reproducible. If the seed cannot be blended, representative samples cannot be drawn. Even skilled and experienced analysts frequently obtain widely divergent results from the same sample. As a result, many of these seeds are refused by the seed trade and most of the movement is through "over-the-fence" transactions.

Erratic seed supplies, lack of adequate distribution through orderly marketing procedures, uncertainty of obtaining good stands, and erratic performances of strains from divergent sources all have contributed to the general failure of the revegetation effort.

3. *Attitudes and Practices*

The livestock producer of the Great Plains has historically fancied himself a livestock manager. A great deal of attention has been paid to breeds and breeding and to the appearance of the animals. Relatively little attention has been paid to the actual performance of the animals, their rate of gain, efficiency of gain, reproductive efficiency and similar traits, and almost no attention has been paid to the performance of the grasses which support the livestock. The idea that a rancher should and must be a grass grower first and a stock grower second is a novel and uncomfortable concept even for some of the leading ranchers of the region. It has been, in fact, an unpalatable idea to many agricultural leaders including research workers, technicians, extension workers, and some administrators. Yet universally, the most serious and chronic problem in the production of livestock is the production of the feed and forage with which to nourish them.

Recent years have seen some marked changes in these respects. Ranchers are coming more and more to know their range plants and to look for changes in botanical composition that indicate trends in range condition. They are looking more toward use of supplemental pastures as a means of lightening the grazing load at critical times. Some have learned to work tame pasture programs into their ranching operations and more are growing additional hay, stover, grain, and silage to round out their feed requirements. Many ranchers understand better the value of deferment of

rangeland and the need for production of surplus grass in moderate grazing. There is a marked tendency for stockmen to think in terms of specific grasses rather than in terms of the older concept of "grass" as a sort of homogenized green material with which nature covers the countryside.

The modern rancher is not only becoming more of a grass expert, he is becoming chemical-minded. Horn flies, grubs, lice, ticks, and screw worms are being controlled much better than in former years. Weeds and brush are being sprayed on an extensive scale in some areas. Stilbestrol implants and antibiotics are commonly used, and protein supplements are much more skillfully used than formerly. Ranchers are intrigued by the possibilities of animal and plant hormones, systemic insecticides, antibiotics, and other wonders of the world of chemistry. They are eager for new developments and quick to take up new practices. More of them have been to college than ever before and many of them have a good basic grasp of the physiology and clinical aspects involved.

The agronomist and the animal husbandman have, in short, a more enlightened, more exacting, and more demanding clientele than they had twenty years ago, and more concrete research results will be expected in the years to come. This will demand closer coordination between the agronomist and the livestock specialist, a higher order of research, more basic and fundamental research into the nature of growth and reproduction of both plants and animals, and greater technical competence on the part of the extension man. All of this is to the good of agriculture and shows that small advances breed a demand for still greater progress.

B. Recent Developments

1. Fertilizing Native Range

Studies in the northern Great Plains have shown that certain types of rangeland respond profitably to nitrogen fertilization (Rogler and Lorenz, 1957). These ranges are primarily along the east side of the Great Plains where western wheatgrass and the stipagrasses are dominant. Farther west where blue grama becomes the dominant grass, responses are not profitable and, in general, warm-season native grasses do not respond sufficiently to nitrogenous fertilizers to pay for the fertilizer (Mader, 1956; Brouse *et al.,* 1954). It is interesting to note that response to nitrogen on rangelands occurs where the total soil nitrogen is high. The cool-season grasses respond early in the spring because of the lack of available nitrogen from nitrification under the low soil temperatures that exist in the north.

2. *Irrigated Pastures*

The acreage of irrigated pasture is increasing slowly throughout the Great Plains. Some combinations are remarkably productive and even small acreages can supply significant amounts of forage. Small grains, sudangrass, and bermudagrass with ladino clover or hairy vetch are especially productive in the south. Bromegrass and alfalfa are the most important species used in irrigated pastures in the north and on the high plains of the south. A few other grasses and legumes such as orchardgrass, Kentucky bluegrass, red and alsike clovers, are used to a limited extent. Irrigated ensilage crops have a considerable potential throughout the Plains in providing substantial quantities of energy and roughage for increased livestock production.

Studies on irrigated and subirrigated pastures and meadows throughout the Great Plains area have shown that significant and profitable increases can be obtained through appropriate fertilizer usage (Brouse *et al.*, 1954) with tame forages such as bromegrass, alfalfa, alsike, and red clover.

3. *Supplemental Crops*

The most efficient use of native rangeland is now being made in conjunction with supplemental pasture and forage crops. Small grain pasture when available and sorghum bundle feed have long been used as supplements to native range in the central and southern Great Plains. The small grain pasture, however, has been largely a byproduct of the wheat industry and much of the sorghum grown has been a compromise between a grain crop and a fodder crop. In recent years rye, barley, oats, and vetch have been established exclusively for grazing on a larger scale, and more sudangrass and forage sorghums are grown entirely for livestock feed. Brome-alfalfa and crested wheat-alfalfa pastures in the North and bermudagrass and blue panic in the South are now being worked into livestock production programs much more skillfully than in the past.

4. *Weed and Brush Control*

Brush control is a problem of enormous magnitude in the southern plains and the control of weeds on rangeland is important wherever grass has been weakened by drought or overgrazing (McIlvain and Savage, 1954). Brush control is not new, but more of it is being done than ever before and in some areas brush is actually being set back faster than it is increasing, finally reversing a trend three-fourths of a century old. The costs are still very high in relation to the productivity of the land and no treatment is altogether satisfactory. A higher return for the money in-

vested can often be obtained from spraying weeds with a herbicide than from any other brush control practice.

5. *New Varieties*

Nordan crested wheatgrass recently released in the northern Great Plains may have a considerable effect on the usage of this species (Rogler, 1954a, b). Its large seed and exceptional seedling vigor give greater assurance of successful stands and may well permit more flexibility in land use. The recent development of improved varieties of native range grasses in Nebraska and Oklahoma may have an even greater effect on the over-all revegetation picture. Those adapted to the southern Great Plains especially, may go a long way toward solving the chronic seed shortage as well as many of the handling, marketing, testing, and labeling problems that have held up the range seeding program for so many years (Harlan *et al.*, 1956). Some exotic species may also have a considerable effect on the utilization of abandoned or marginal cropland in the South. Blue panic, the Old World bluestems, and some of the lovegrasses are finding a place, and in southern Texas buffelgrass is being used on rangeland as well as in tame pastures.

C. Research Problems

1. *The Utilization of Forage by Ruminants*

Both the improvement of forage plants and the development of better management practices will depend to a large degree on a better understanding of how they are used and what constitutes good forage. Low gains are often obtained even when ample forage is available. The underlying causes need to be understood before much can be done to correct the situation.

2. *The Revegetation of Degraded Rangelands*

Reasonably satisfactory methods are available for establishing range grasses on plowable land (Stoesz, 1952; McWilliams, 1955; McIlvain and Savage, 1954). There are millions of acres too rough, too stony, or too gullied and eroded to cultivate. Many of these ranges have been overgrazed to the point that deferment will not restore them in any reasonable length of time. Rangelands of this type constitute one of the most serious problems in Great Plains agriculture today. Special plant strains are needed that are so aggressive under these conditions that they can become established without a seedbed and thrive sufficiently to at least start a succession toward recovery. Research along these lines is being conducted on the Old World bluestems in Oklahoma.

3. Control of Woody Plants

Present methods often cost 12 to 16 dollars per acre for partial and temporary control of brush on land that under ideal conditions will yield no more than 60 lb. of beef per acre. Though the practice sometimes pays for itself in increased production, there is no over-riding incentive even with a government subsidy on the practice. Better methods are needed and sufficient work has now been done on the problem that future progress will probably come as a result of fundamental investigations into the physiological and biochemical aspects of the problem.

4. Grass Seed Production

With the increase in irrigated acreage throughout the Plains has come a demand for more high return crops. Grass seed is a potential cash crop of high value and the product is in great demand for range and pasture seedings (Harlan *et al.*, 1956). Studies underway have shown that high yields of switchgrass, side-oats grama, buffalograss, sand lovegrass, blue panic, smooth brome, indiangrass, and several others can be obtained with careful management. More precise information is required on soil amendments, watering regimes, harvesting, cleaning and processing procedures, and similar subjects.

5. The Properties of Grass Seeds

Appropriate procedures for testing and labeling many range seeds are not known (Harlan, 1957). Optimum temperature and light regimes, germination media, methods of breaking dormancy, methods of determining purity, methods of sampling, and numerous associated problems have not been worked out for a number of species. The nature and duration of dormancy, conditions for optimum seedling growth, the effect of various degrees of processing on germination and field performance are areas totally unexplored for many of the range plants.

6. Better Ways of Getting Stands

Stand failures in range seedings are extremely costly. The seed is usually high priced in relation to the land value, and time lost in failures may be considerable. In the widely accepted stubble mulch method, one year is spent preparing a seedbed. Two additional years may be lost in determining whether or not a stand was obtained. A failure requires that the entire procedure be repeated. Failures are due to a variety of causes, e.g., poor seed, poor seeding equipment, crusting of the soil, drying out after seeds have sprouted, grasshoppers, competition with weeds, etc. Many of these problems can be solved with information at hand, but intensive re-

search on stand establishment may reveal more efficient practices than those now in use.

7. *Breeding Behavior of Range Grasses*

Progress has been made in improving both native and exotic grasses but still greater improvement will, in many cases, depend upon a better understanding of the genetics, cytology and cytogenetics of the species in question (Hanson and Carnahan, 1956). More basic work also is needed in the area of physiology and ecology insofar as there are under genetic control.

8. *Breeding and Improvement of Grasses*

Some of the more serious problems may be solved by the development of superior forage varieties. Greater assurance of obtaining stands may come with the development of grasses with larger seed size and greater seedling vigor (Kneebone, 1956; Kneebone and Cremer, 1955; Rogler, 1954a, b). Some seed production problems could be solved by varieties that give higher seed yields under cultivation and which are resistant to shattering at maturity. The reduction or elimination of seed appendages and the development of varieties with less new-seed dormancy could do much to reduce the technical difficulties of seed handling and marketing as well as improve the chances of establishment. Hardier and more persistent varieties better suited to survival and propagation under grazing could do much to reclaim degraded rangeland.

IV. Soil Moisture Conservation

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A. Introduction

Utilization of the Great Plains by man for habitation, agricultural production, and industrial expansion is most frequently limited by low moisture supply. For more intensive utilization, moisture conservation must receive high priority. People's opinions differ as to what the term moisture conservation means, but they would generally agree that moisture is conserved when:

1. The proportion of the precipitation available for transpiration by plants is increased.
2. The amount of useful plant products produced per unit of moisture is increased.

3. Moisture above the field capacity of the root zone of plants is passed through the soil and contributes to permanent underground reservoirs or to streamflow.

The Great Plains have been occupied by white man for 50 to 100 years. During this time, his major contributions to moisture conservation have been (1) the introduction of better-adapted crops, (2) improved control of weeds that compete with crops for moisture, and (3) mechanization to an extent that allows one operator efficiently to handle large units, using timely tillage operations. The latter item probably contributes more to manpower efficiency than to water-use efficiency.

This section on moisture conservation is directed at the use of water where it falls, since this is in agreement with current practice in the Great Plains. Although the major part of the discussion deals with a system of tillage usually known as dryland farming, much of the information presented can be applied to the extensive areas of range lands.

B. Present Situation and Practices for Moisture Conservation

1. *Efficiency of Summer-Fallow*

Data are available on the efficiency of water storage under summer-fallow from 23 dryland stations which were operated over the Great Plains by the U.S. Department of Agriculture in cooperation with the State Experiment Stations. In summarizing the data, Mathews and Cole (1938) found an average storage at the end of the fallow period of only 20 to 25 per cent of the precipitation that fell during the fallow period. Thysell (1938) found that at Mandan, North Dakota, the rainfall during the approximately 20-month fallow periods ending about April 20 of the years 1916 to 1934 varied between 16.67 and 31.58 inches. Water stored in the soil during these fallow periods varied from 1.01 to 9.07 inches. The second driest year had above-average moisture storage, whereas the year with the lowest moisture storage had almost average rainfall. Thus there is not a close relationship between total precipitation and moisture storage. Low moisture storage efficiency is due to the high proportion of the total precipitation which comes as small rains and the high proportion of these rains that is lost by evaporation.

2. *Rainfall Characteristics*

An excellent summary of rainfall characteristics for Kansas is presented by Robb (1938). These data for the western third of the state are typical of the distribution pattern of the Plains area. As an average, rain fell about once a week, but 60 per cent of the rains brought one-fourth inch or less

of precipitation. One rain per year yielded between 1.0 and 1.5 inches, and rains of between 1.5 and 2.0 inches occurred in only one-half of the years. The solution to the problem of moisture conservation in the area will be found in increasing the effectiveness of the precipitation that comes in amounts less than one inch.

3. Stored Moisture and Crop Yields

Throughout the Great Plains area there is a good relationship between the amount of water stored in the soil at seeding time and the ultimate yield of the crop. This holds true whether the crop is grown each year or alternately with fallow. The relationship between crop yield and stored moisture is much better on fallowed land than on continuously cropped land because stored moisture makes up a larger proportion of the moisture available to the crop. For winter crops, principally winter wheat, the fallow period is 13 to 15 months long, but for spring-seeded crops it may extend up to 20 months.

Hallsted and Mathews (1936) prepared a table to show the odds of obtaining yields within various yield groups in relation to stored moisture. When winter wheat was seeded in soil without available moisture in the profile in western Kansas it yielded less than 4 bushels per acre 71 per cent of the time, but when the soil was wet to 3 feet or more at seeding time, the yield exceeded 20 bushels per acre 70 per cent of the time. It is obvious that the amount of available water stored in a foot of soil is important in such a relationship. Once the relationship between the depth of stored moisture and crop yield for any piece of land has been established, the stored moisture at seeding time is indicative of the yield. Such a measurement is helpful in planning farm operations. Cole (1938), using crop yields for 275 station-years from 14 stations in the spring wheat area of the northern Plains, found the average yield on fallow land was 18.54 bushels per acre, whereas continuously cropped land produced an average yield of 11.16 bushels per acre.

Cole and Mathews (1923) pointed out that the greater the amount of water used by spring wheat, the more efficiently it is used. By grouping grain plus straw yield data for 83 station-years into 1000-pound yield increments, the water required to produce one pound of dry matter progressively decreased as the yield increased. When yields were less than 1000 lb. per acre, 2165 lb. of water were used to produce each pound of dry matter in comparison with 754 pounds for crop yields ranging between 4001 and 5000 lb. Barnes (1938) found it took 2000 lb. of water for each pound of wheat grain produced under continuous cropping but only 1350 lb. of water per pound of grain for wheat grown on fallow land in southern Saskatchewan.

4. *Weed Control*

It is well established that both fallow and cropped land must be kept free of weeds to obtain the highest efficiency of moisture storage or use. One large weed per square rod can draw moisture from the entire moist layer. Large acreages of crop land are now consistently sprayed to kill weeds as a moisture-conserving measure. Both airplane spraying and the use of ground equipment with booms up to 60 feet or more in width are common in the Great Plains.

5. *Deep Percolation*

In semiarid areas, the precipitation rarely is adequate to utilize completely the moisture storage capacity of the soil even following a season of fallow. Stored moisture takes the form of a mantle of moist soil in the upper part of the soil profile, which varies in thickness with the amount of moisture stored. The soil under this mantle has been dried to the wilting point by previous crops. The prevalence of the dry layer shows that deep percolation of water is generally an insignificant source of water loss.

6. *Use of Water for Transpiration*

Under normal cropping conditions, it has been impossible to reliably separate transpiration losses from direct evaporation losses. Hide (1954) estimated that the proportion of the precipitation that is transpired may be as low as 20 to 25 per cent. Recent unpublished data by other workers indicate that the figures may be slightly low, but the efficiency probably does not exceed 35 per cent.

7. *Runoff Control*

In areas of acute moisture shortage, the reduction of runoff from occasional intense showers is a logical source of additional moisture. The Soil Conservation Service has activated a strong program to reduce runoff in the Great Plains. Major efforts have been along the lines of: (1) Cropping and tillage methods which maintain either crop or crop residue on the surface at all times. (2) Contour tillage supported by strip cropping. (3) Terracing.

Crop or residue on the surface not only protects the soil surface from dispersion by the beating action of rain and the consequent reduction in infiltration, but it also slows the flow of water over the surface, allowing more time for infiltration. Musgrave (1941) provided data for the Great Plains sites of Hays, Kansas, and Spur, Texas, each of which has an annual rainfall of approximately 20 inches. Runoff from clean-tilled crops approximated 16 per cent of the rainfall, whereas under dense crop growth, it

amounted to only about 5 per cent of the precipitation. Thus a good cover prevented the loss of about 10 per cent of the 20-inch rainfall, or 2 inches of water. Similarly, Fisher and Burnett (1953) found that, over a 16-year period, placing rows on the contour stored about one-fourth of an inch more water than where the rows were up and down the slope. This is 5 to 10 per cent of the amount of water stored during a fallow period throughout the Plains.

In areas where the soil is fairly permeable and torrential storms which may cause terrace breaks are infrequent, the level terrace is used as a moisture-conserving method. The level terrace is usually of the ridge type and is constructed without grade so that runoff water accumulates above it. Runoff water from the area between terraces is held in the terrace channel until it infiltrates into the soil. These terraces are sometimes constructed with closed ends so that no water escapes.

In most of the northern Plains, a major part of the runoff is from snow-melt. During the winter the terrace channel fills with snow and ice, and the structure is ineffective during the period of greatest need.

Under some systems of land management runoff can cause serious loss of water. Yet in the Great Plains, runoff control is not a large potential source of additional moisture. Langbein and Wells (1955) show that runoff as calculated from streamflow causes a loss of less than 1 inch of water per year over most of the Plains. Streamflow is probably a conservative measure of runoff since part of the loss from an area may be infiltrated into other areas before it reaches the measuring station.

8. *Water Erosion*

The water erosion problem within the Great Plains is, in most characteristics, similar to that of other regions. Although runoff tends to be small in comparison with other areas, the soils are mostly of the Chestnut and Brown great soil groups and are not as resistant to water erosion as the darker soils to the east of the area. Under the limited moisture situation, plant cover is usually rather sparse. Large areas of fallow are devoid of living plants although several million acres of fallow land are tilled to leave crop residues on the surface for soil protection. Even though total runoff is small in comparison with that of more humid areas, water erosion frequently becomes a serious problem.

9. *Evaporation*

It has been shown (Section IV-B1 and 6) that water storage in fallow or its use by crops accounts for only 20 to 35 per cent of the rain that falls in the Plains. Runoff usually accounts for less than 6 per cent of an average annual rainfall of about 17 inches for the entire Plains, and deep percola-

tion causes only extremely small losses of water. Thus direct evaporation from the soil must account for a loss of between 60 and 75 per cent of the total precipitation that falls on the area. This potential source of water has received almost no attention since it was found (about 1920) that the dust or clod mulch was not an effective means of moisture conservation.

C. Recent Developments for Moisture Conservation

To understand recent developments, it is necessary to be familiar with the evolution of research in the Great Plains. Beginning early in the twentieth century, the State Experiment Stations directed limited research at the problems of the Great Plains. The work of Alway (1913) was probably the most comprehensive. Subsequent to 1905, 23 "dryland" stations were activated over the Great Plains by the U.S. Department of Agriculture, cooperating with the State Agricultural Experiment Stations. The work at these stations was directed mostly at the effect of tillage treatments, crop species, and crop rotations on crop yields and moisture use. These studies have made an important contribution to our understanding of the area, particularly with regard to climate and its influence on crop sequence, water storage and use to produce crops.

In the early years this work was supported by such fundamental soil moisture studies as the development of the moisture equivalent to aid in the characterization of the moisture relations of soils by Briggs and McLane (1907). Buckingham (1907) also developed the concept of capillary potential to explain the movement of soil moisture. In this paper, he also showed that soils which were dried rapidly, as would occur under arid conditions, lost less moisture in a drying cycle than when they were dried more slowly. Buckingham's study was evidently directed at moisture problems of the Great Plains. The emphasis on basic work appears to have decreased after about 1915, although the field studies were continued at most of the stations until about the end of World War II.

Research conducted by the Soil Conservation Service on the effect of erosion and runoff control practices such as residue management, strip cropping, contour tillage, and the use of terraces on crop production started about 1930. Also about 1930, our knowledge of the moisture relationships of soils began to expand rapidly. However, application of this new knowledge was directed mostly at the humid and irrigated areas of the country. It was not until the end of World War II that intensive studies were undertaken to develop a better understanding of basic factors in moisture conservation and utilization in the Great Plains. Much of the systematized field work at the old dryland stations was discontinued by the U.S. Department of Agriculture in favor of studies that would provide better information on the factors that influenced the efficient use of soil

moisture. About this time, the State Experiment Stations in the Plains states began to expand and actively work on the moisture problems of the Plains. This expansion in activities has been so recent that results of the work are only starting to appear in print.

1. Climatic Factors

An outstanding series of studies has been conducted at Swift Current, Saskatchewan, Canada, using closed tanks 15 inches in diameter and 60 inches deep to grow spring wheat. Comparisons between continuous wheat, wheat on fallow, and two crops of wheat succeeding fallow are available. These tanks have been weighed periodically to follow moisture changes during both the crop season and the fallow period. Growth and moisture use on adjacent, similarly treated field plots have been followed to ascertain that the tanks were reasonably representative of field conditions. With regard to this study, Staple and Lehane (1954) reported that, over a thirty-one-year period, stored moisture and growing season rainfall were about equally effective in producing crop yields. In the field plots, they found a positive curvilinear relationship between evapo-transpiration and crop yields showing high moisture-use efficiency in the years of high evapo-transpiration. Thus high yields and low evapo-transpiration per unit of yield occurred in those years when sufficient moisture was available to allow high total evapo-transpiration. The yields obtained from the tanks were reduced significantly by above-normal temperatures.

It has been recognized generally that the lower temperatures which prevail in the northern Plains increase the efficiency of water use by crops above that found in the southern Plains. It is well established that a specific Great Soil Group develops under lower rainfall in the northern regions than in southern regions. Yet the effect of temperature on the efficiency of water use by crops has not received much attention. Army and Ostle (1957) found that evapo-transpiration of spring wheat was reduced by the same factors that increased evaporation from a free-water surface. The years with the greatest evaporation from a free-water surface are the hot, dry years which provide little water for either direct evaporation from the soil or for transpiration through plants.

An intriguing method of getting at moisture efficiency was reported by Fisher and Burnett (1953). Small lysimeters were filled to a depth of 2, 4, and 8 inches with fine sandy loam, with clay loam, and with well-rotted manure. The amount of water that passed through each lysimeter was measured. Although abnormal boundary conditions were introduced, it appears that the moisture percolating through the various depths should approximate the amount of moisture that would be stored at soil depths greater than the depth of material in the lysimeters. The clay and sandy soils al-

lowed respectively 30 and 40 per cent of the water to pass a 2-inch layer of soil, but only about 40 per cent of these amounts passed through the 8-inch layer. In contrast, 58.5 per cent of the rainfall passed through the 2 inches of manure and 51.8 per cent through 8 inches. Manure was three to four times as effective in allowing water to percolate through an 8-inch layer as was either the sand or clay. Figure 3 presents the percentages of the rainfall which came in different sized groups over a 4-year period and penetrated the 4-inch layer of the three materials. The high efficiency of

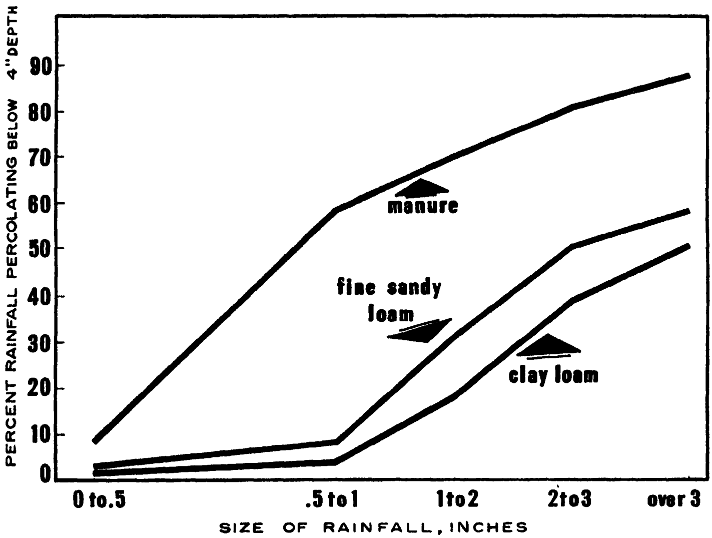

FIG. 3. Effect of size of rainfall on per cent of rainfall percolating through 4-inch layers of three materials. (Fisher and Burnett, 1953.)

manure in allowing percolation from small rains is apparent. A knowledge of the factors that contribute to this high efficiency could suggest methods of modifying soils to greatly increase water storage efficiency and thus moisture conservation.

Hide[1] found that the natural summer drying pattern of the upper 3 inches of three soils placed side by side differed considerably. The difference in drying pattern of two soils is presented in Figs. 4 and 5. It is evident that Huffine silt loam lost water rapidly from the different soil layers, after which loss almost ceased. The Bridger clay loam lost water over a longer period of time at a progressively decreasing rate. The upper 3

[1] Hide, J. C. Unpublished data from paper presented before the Soil Science Society of America (Atlanta, Georgia), November, 1957.

inches of Bridger soil lost about 0.75 inch of water in a drying cycle, whereas Huffine lost only about 0.50 inch. An explanation of the properties that account for these differences is not available, but a knowledge of the variables which cause this difference may aid in devising soil treatments that will increase moisture conservation. Lemon (1956) showed that surfactants offer possibilities of modifying soil properties in a way that would decrease capillary flow back to the surface and reduce water losses.

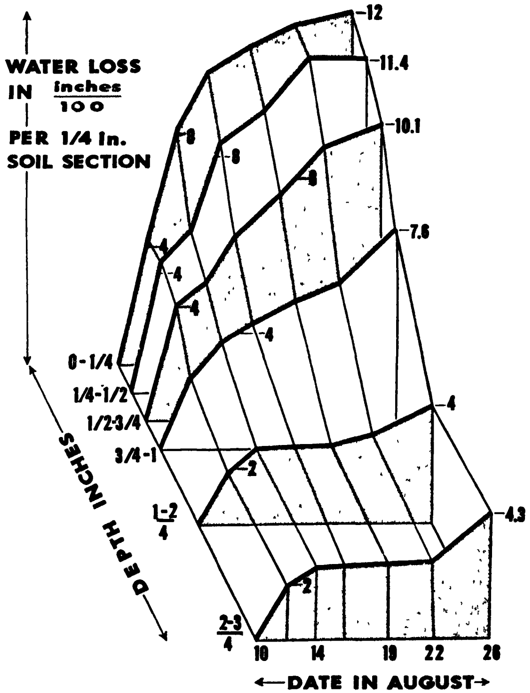

FIG. 4. Moisture loss with time from different layers of the upper 3 inches of Bridger clay loam soil in a natural drying cycle.

2. *Trash Cover*

There has been considerable difference of opinion on the effectiveness of trash cover on the efficiency of moisture storage in fallow. In studies conducted in northeastern Montana, Aasheim (1949) found that leaving crop residue on the surface during the fallow period in contrast to plowing it down had very little influence on the amount of water stored in the

soil at the end of the fallow period. However, in north-central Montana, there was a slight difference in favor of leaving the residue on the surface. In Texas, Porter *et al.* (1952) found that leaving crop residues on the surface is considerably more favorable to moisture storage than plowing them down whether the land is continuously cropped or alternately fallowed. Climatic or soil variables apparently determine the effect of residue man-

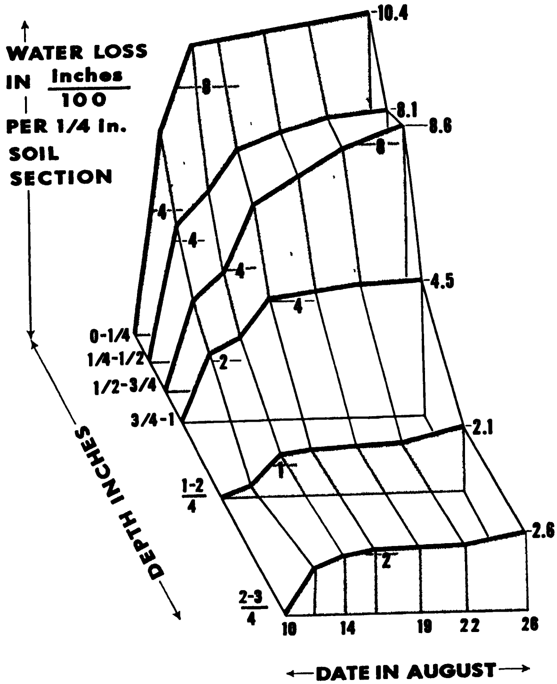

FIG. 5. Moisture loss with time from different layers of the upper 3 inches of Huffine silt loam soil in a natural drying cycle.

agement on moisture storage efficiency. Crop residue on the surface may either increase or have little effect on moisture storage but is extremely important from the standpoint of erosion control.

3. *Plant Stand*

In moving from a humid to an arid area, native plants tend to space themselves farther and farther apart to increase the water available to each plant. In semiarid areas, crops planted annually do not occupy the land long enough to make a similar adjustment. If such an adjustment is

to be made, it must be done through seeding rate. It appears logical that there should be an optimum number of plants and plant spacing to make the most efficient use of water under any situation. Brown (1956) showed this to be true for the sorghum crop. He found that the optimum plant stand and spacing are influenced by the amount of water stored in the soil at seeding time and the amount of growing season rainfall. Though many seeding rate studies have been made with wheat, the results have usually been less informative because of the tremendous capacity of the wheat plant to tiller in situations where plant competition is low. This tillering usually occurs before the plant encounters much moisture stress.

4. *Fertilizers*

During most of the time that the Great Plains has been farmed, it was believed that the use of commercial fertilizers could not be justified. However, during the past several years there has been an increase in the amount of fertilizer used, and their use is profitable in many areas. Since the available moisture is usually exhausted at harvest time, it is obvious that an increase in yield from the use of fertilizers must be a moisture-conserving measure. Zubriski and Norum (1955) found that fertilized plots did not deplete the soil moisture to a greater degree than unfertilized plots when yield increases of spring wheat of between 0.9 and 9.6 bushels per acre were obtained. Kmoch *et al.* (1957) showed that nitrogen fertilization increased root weights at nearly all soil depths and permitted more complete utilization of available subsoil moisture.

5. *Crop Sequence*

In some areas of the Plains, greater efficiency in water use is attained by growing a simple sequence of crops than by cropping continuously to one crop or alternating one crop with fallow. In sections of the spring wheat area, adapted corn varieties can be used to replace fallow without seriously reducing wheat yields. Good results have been secured from a three-year rotation of winter wheat, sorghum, and fallow. This cropping sequence provides a considerable period for moisture storage ahead of planting time for each crop and yet produces two crops in three years. Mathews and Cole (1938) discussed factors involved in using crop sequence to increase the efficiency of moisture use in the Great Plains.

D. Research Problems

With the increased emphasis that has taken place on research in the Great Plains during the past ten years, some of the problems outlined below are receiving limited attention.

1. *Inducing Rainfall*

Increasing the amount of water available for crop production is a major problem of the area. The possibility of inducing additional rainfall has attracted attention, but authorities seem to agree that results up to the present time are inconclusive. Since it is generally agreed that little can be done to induce precipitation under conditions that produce drought, perhaps modification of the general circulation of the atmosphere by man will be necessary before extended, disastrous dry spells can be prevented.

2. *Dew*

The second source of moisture in the area is from dew, and little is known about this source of water. Neuman (1956) found that dew on the coastal plain of Israel amounts to about 0.16 mm. per day throughout the year. This would amount to about 2.5 inches of water per year and is considerably under the 9 inches measured in Ohio by Harrold and Dreibelbis (1951) through change in weights of monolith lysimeters. Although the climate of the two areas differs widely, the latter measurements include moisture condensed in the soil, in addition to the actual water collected on plants above the soil or in the soil itself. It is well established that the surface soil undergoes a diurnal fluctuation in its moisture content even in the absence of dew. Indications that some of this condensed water is distilled into the soil is presented by Hide (1954). Stone (1957) showed that artificial dew prolonged the life of pine seedlings under extreme drought conditions. There is little data on the amounts of dew or condensation that occur or their importance in crop production in the Great Plains.

3. *Evaporation*

Present information indicates that better use of the water now precipitated on the Great Plains will continue to be the main source of water for crop growth. Evaporation is a major source of loss, and more intensive studies on the process of evaporation loss and methods of its control are justified. There is evidence that evaporation losses differ with soil properties, cover, and weather pattern. Probably conditions that reduce evaporation during part of the year encourage it during other parts of the year. Evans and Lemon (1957) discuss the net energy concept of studying moisture phenomena, and this approach deserves intensive study. However, it has the disadvantage of not separating evaporation from transpiration. Many of our studies are vitally concerned with the portion of the water that is actually used by plants. Thus a method which will measure evaporation and transpiration separately is vitally needed.

4. *Instrumentation*

Our inability to accurately measure the content of moisture in a soil because of soil variability complicates moisture studies. Barnes (1938) found variability of up to 3 to 5 per cent in actual moisture content in samples taken at 1-foot-depth from adjacent holes. A device that would integrate the moisture content through a column of soil 4 to 10 feet wide would be invaluable in studying moisture use by plants. For efficient use, such an instrument should measure soil moisture at frequent intervals without injuring growing crops. It should accurately measure the moisture in a 2-inch-depth increment of soil.

5. *Runoff*

Although runoff from the Plains is comparatively low (see Section IV, B7), water is so critical in the area that methods of reducing the loss cannot be ignored. A. W. Zingg has modified the level terrace in experimental studies at Amarillo, Texas, so that the terrace channel is broad and flat, according to Evans and Lemon (1957). It seems probable that such a channel may contribute to increased efficiency in the use of collected runoff water.

6. *Snow*

The amount of snow that falls decreases from north to south, and in the northern section a major part of the winter precipitation comes as snow. Since this snow usually covers frozen ground, the conservation of snowmelt presents special problems. It is accepted in the area that the presence of enough crop residue on the surface to hold snow is a moisture-conserving measure. However, our knowledge of methods of conserving moisture from snow cover is inadequate.

7. *Plant Growth Pattern*

A great many studies have been made on water use by plants. Yet we are still far from having detailed knowledge of how to obtain the most yield from a limited water supply. In grain crops, it appears that vegetative growth should be reduced to allow a maximum amount of water for maturing the seed. Further research is needed to determine if this objective can be best attained through proper plant spacing, genetic control, or the control of soil fertility.

8. *Plant Breeding*

The plant breeder usually has measured the adaptability of a crop variety to an area by comparing it with other varieties. However, the plant grows in a series of stages and, for maximum efficiency, each stage

must make its maximum contribution to efficient yield. Until it is known how each stage should contribute to the efficient use of water for final maximum yield and quality, varieties cannot be developed having maximum adaptation to an area in which the moisture supply is limited.

9. *Fertilizers*

Commercial fertilizers have not been used extensively in the Great Plains, although their use is now increasing. Fertilizer practices have been brought into the Plains from humid areas where it is usual to fertilize for rapid growth throughout the season since this usually produces the greatest yield. In an area of limited water supply, the objective should be to fertilize for maximum water-use efficiency. This may call for drastic modifications in fertilizer practice.

10. *Tillage Equipment*

The type of tillage equipment used in preparing land for seeding or during the summer-fallow operation has not usually had much influence on water storage or crop yield, provided it controlled weeds and prepared a satisfactory seedbed. When the desirable soil properties for efficient water storage are known, it is probable that tillage methods can be devised to aid in achieving these properties.

Water supplies as a possible limiting factor in the expansion of national economy are now receiving attention. Although the Great Plains is a semiarid area, it is doubtful if its water supply is used at near its maximum efficiency.

V. Soil Fertility Problems

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Soil fertility problems exist in the Great Plains, under both dryland and irrigated conditions. Studies of nutrient element levels for optimum crop production suggest that nitrogen and phosphorus are the elements most likely to be deficient. This is further borne out by experiments on crop response to legumes in the cropping system, manure application, and the use of commercial fertilizers. The increased use of fertilizers in the Great Plains reflects the nutrient element status of the soils as well as advances in the knowledge of fertilizer practice and technology.

A. Nitrogen Status of Great Plains Soils

Much of the land in the Great Plains area has been cultivated less than sixty years. This has been long enough, however, to result in appreciable

losses of soil nitrogen, especially under certain management practices. It should be pointed out that soil nitrogen losses result from decomposition processes, leaching, crop removal and erosion as influenced by the cropping, tillage, and fertilization practices followed. Losses from both wind and water erosion occur in the Great Plains.

1. Losses from Dryland Soils

Nitrogen losses from surface soils of 9 to 62 per cent of that present in virgin soils have been reported for periods of cultivation ranging from twenty-five to forty-one years by Harper (1946), Chang (1950), Hill (1954), Fine (1956), Rhoades (1956), Hobbs and Brown (1957), and Haas *et al.* (1957). These losses appear to be conservative for cultivated lands in the Great Plains since erosion losses have been slight to moderate at most of the sites studied.

Cropping practice on dryland soils had a marked influence on soil nitrogen losses (Hill, 1954; Rhoades, 1956; Hobbs and Brown, 1957; and Haas *et al.*, 1957). In general, nitrogen losses from the soil increased as the proportion of intertilled crops increased. The greater tilling of the soil with the latter crops no doubt intensified the decomposition of soil organic matter, with an accompanying loss of nitrogen. Fallowing when associated with intertilled crops had an effect on nitrogen losses similar to that of continuous intertilled crops. However, nitrogen losses have generally been only slightly greater for a cropping system of alternate small grains and fallow than for a cropping system of continuous small grains.

Grasses and alfalfa in the cropping system reduced soil nitrogen losses but were not effective in maintaining soil nitrogen at the original level (Haas *et al.*, 1957). Neither rye nor legumes other than alfalfa used as green manures were effective in reducing losses of soil nitrogen.

McHenry *et al.* (1947) studied nitrogen maintenance in a chernozem soil at North Platte, Nebraska, as influenced by the proportion of time in a perennial grass sod. Soil nitrogen losses were less where four or more years of grass were included during a period of nine years than where a rotation of grain crops and fallow was followed. However, losses of nitrogen were so small where the land was in grass for seven or more years out of nine that nitrogen maintenance was suggested.

Applications of barnyard manure reduced nitrogen losses at all locations studied by Haas *et al.* (1957). There was an increase in nitrogen content of the soil due to manure applications at only 1 of 12 locations. Average losses of nitrogen in comparable rotations were 25 per cent where manure was applied and 37 per cent where no manure was applied.

Carpenter *et al.* (1952) studied the relationship between total soil nitrogen content of the rotation plots at Mandan, North Dakota, and

nitrogen availability to wheat under field conditions. They obtained high positive correlations between grain yields and the quantity of nitrogen in the wheat plants at all stages of growth, with the amount of plant nitrogen at jointing giving the highest correlation. Although a significant positive correlation was obtained between soil nitrogen and grain yield, the relationship was not as close as between nitrogen uptake and grain yield. Nitrogen uptake by the wheat plants fell off rapidly after they reached the jointing stage on low-nitrogen soils while uptake continued on the high-nitrogen soils. Presumably this difference was related to the capacity of the soils to produce nitrate, as suggested by the work of Allison and Sterling (1949) for soils from the same rotation plots. Haas *et al.* (1957) reported a highly significant positive correlation of 0.562 between total soil nitrogen and nitrate production in 214 samples from 13 locations in the Great Plains during a six-week incubation period.

2. *Losses from Irrigated Soils*

Nitrogen losses may be appreciable on irrigated land where little attention is given to manure applications and the use of legumes in the cropping system. Weakly and Nelson (1950) reported that both manure applications and the use of alfalfa in the cropping system materially aided the maintenance of soil nitrogen in an irrigated clay soil at Newell, South Dakota. Nitrogen changes in the surface foot of an irrigated chestnut soil at Mitchell, Nebraska, during the 30-year period from 1912 to 1942 (Kubota *et al.*, 1948), are given in Table III.

TABLE III

Nitrogen Changes in the Surface Foot of an Irrigated Chestnut Soil at Mitchell, Nebraska, During the 30-Year Period from 1912 to 1942

Length of rotation in years	Years of legumes per rotation	Mean annual application of manure (tons per acre)	Loss (−) or gain (+) in nitrogen (%)
2	None	6	+4
6	3	2	+2
6	3	None	−8
3	None	4	−12
2 & 3	None	None	−32

It seems evident that consideration should be given to the use of legumes in the cropping system, to applying manure, and to applying nitrogen fertilizer for supplying adequate nitrogen to non-legume crops grown

on irrigated land in the Great Plains. Some soils are so low in nitrogen when they are first placed under irrigation that immediate attention must be given to supplying nitrogen. Other soils may contain sufficient nitrogen to supply the crop with adequate nitrogen for several years.

B. Phosphorus Status of Great Plains Soils

Great Plains soils vary markedly in their capacity to supply crops with adequate phosphorus, as indicated by marked differences in crop response to phosphate fertilizer (Peterson *et al.*, 1953). In addition, soil test summaries such as those reported by Dregne and Maker (1955) in New Mexico, and Knudsen (1956) in Nebraska, show noticeable variations in available phosphorus levels.

1. Relation to Kind of Soil

Peterson *et al.* (1953) pointed out that phosphate response by crops in the West has not generally been related to specific soils and soil properties. However, Olson and Rhoades (1953) obtained a reasonably close relationship between soil series and the response of winter wheat to applications of phosphate in Nebraska. In addition, Olson *et al.* (1954) showed a close relationship between soil series in Nebraska and the amounts of available phosphorus obtained by several methods. It seems reasonable to assume that among-series variations in available phosphorus might be greater than within-series variations where similar management practices were followed. In contrast, the reverse might be true where markedly different management practices were followed.

2. Relation to Past Cropping and Fertilizer Practices

Grunes *et al.* (1955) studied the influence of long-time dryland cropping systems on available phosphorus in Cheyenne fine sandy loam at Mandan, North Dakota. Virgin soils and soils from the nonmanured rotations were somewhat low but approximately equal in available phosphorus content. In contrast, soil nitrogen decreased considerably during thirty-eight years of growing grain crops without manure application. Available phosphorus was increased appreciably by manure applications, the increase being related to the amount of manure applied. Phosphorus A values, total uptake of phosphorus by plants, growth response to applications of phosphate fertilizers, $NaHCO_3$-soluble phosphorus, K_2CO_3-soluble phosphorus, and water-soluble phosphorus, all appeared to be satisfactory methods of assessing the phosphorus status of Cheyenne fine sandy loam.

Olsen *et al.* (1954) evaluated residual phosphorus due to applications

of phosphate fertilizer and manure in long-time rotation studies on irrigated Fort Collins loam at Fort Collins, Colorado, Pryor silty clay at Huntley, Montana, and Tripp very fine sandy loam at Mitchell, Nebraska. Four chemical extraction methods of evaluating available phosphorus, Bray and Kurtz No. 1, $NaHCO_3$, water, and surface phosphate were highly correlated with A values. The CO_2 method showed a lower correlation with A values than the other chemical methods. Relative efficiency values of the residual phosphorus indicated by increases in A values expressed as percentages of the increases in total phosphorus due to past phosphate and manure applications were 26 to 30 per cent in Fort Collins loam, 15 to 38 per cent in Pryor silty clay, and 40 to 56 per cent in Tripp very fine sandy loam. Rhoades and Harris (1954) also pointed out that manure applications had a marked influence on total and soluble phosphorus in Tripp very fine sandy loam.

C. Potassium Status of Great Plains Soils

It is recognized that potassium levels in Great Plains soils are generally adequate for optimum crop production. Soil test summaries such as those for New Mexico by Dregne and Maker (1955) and for Nebraska by Knudsen (1956) show that the soils in those states contain appreciable quantities of available potassium. Reitemeier *et al.* (1950) found large reserves of readily available nonexchangeable potassium in soils from rotation plots at three locations in the northern Great Plains. The availability of these reserves was maintained even though exchangeable potassium had been reduced by certain cropping practices. Fertilizer recommendations in different states, such as the recommendations reported for Montana by Shaw and Klages (1956), for Wyoming by Mellor *et al.* (1956), and for Kansas by Smith (1956), point out that potassium fertilizer is not likely to be needed for crop production in the Great Plains. These recommendations reflect the results of fertilizer experiments and soil tests.

A few instances have been reported where increased yields have been obtained from the use of potassium fertilizer on Great Plains soils. For example, Quinby and Fisher (1955) found in fertilizer tests conducted for five years on Miles sand near Chilicothe, Texas, that cotton, castor beans, and sorghums responded profitably to nitrogen, phosphorus, and potassium applied in combination. A low level of exchangeable potassium would be expected in this sandy soil. Larson (1954) reported increased yields of sugar beets due to potassium fertilizer on irrigated calcareous soils in Montana containing large quantities of exchangeable potassium. He presented evidence to suggest that potassium intake by sugar beets was reduced in these soils by a lack of aeration.

D. Status of Other Nutrient Elements in Great Plains Soils

Great Plains soils generally contain adequate quantities of calcium, magnesium and sulfur for optimum crop production. However, some soils in the Great Plains area of Nebraska were sufficiently acid according to the soil tests reported by Knudsen (1956) that lime was recommended for obtaining stands of sweet clover. Magnesium deficiency symptoms on irrigated corn grown on calcareous soils were observed in Nebraska and were corrected by an application of magnesium sulfate. Alfalfa responded to applications of elemental sulfur and gypsum on some acid sandy soils in north central Nebraska.

Many ornamental trees and shrubs, fruit trees, and certain field crops develop a chlorosis when grown on some calcareous soils in the Great Plains area. This chlorosis may be due to iron deficiency interacting with other soil factors. Olson and Carlson (1950) pointed out that sorghums are more susceptible to iron chlorosis than most field crops but are less susceptible than many trees and shrubs. They found that iron chlorosis was not restricted to calcareous soils in Kansas. However, there was a reasonably close relationship between the soluble iron content of the soil and the development of chlorosis. They pointed out that low water-soluble iron content, high manganese-iron ratio, high pH, and the presence of calcium carbonate enhanced the development of iron chlorosis in plants but that other factors determined whether or not chlorosis actually developed. In a later study with sorghums, Carlson and Olson (1951) did not find any relationship between manganese-iron ratios in culture solutions and iron content in the plant. Brown and Holmes (1956) studied iron chlorosis of sorghum and corn grown in three calcareous soils from Kansas, Oklahoma, and Utah. They found that the water-soluble iron content of the soil was somewhat useful as an index of iron deficiency. However, the kind and variety of the plant had to be considered in using the information. Iron chlorosis developed in WHEATLAND sorghum and PI-54619-5-1 soybeans grown on the soils from Kansas and Oklahoma and in PI-54619-5-1 soybeans grown on the soil from Utah. HAWKEYE soybeans developed normally on all three soils.

Criddle and Haise (1957) reported that zinc-deficient corn was observed in North Dakota on Gardena subsoils that had been exposed by leveling operations. An application of zinc sulfate removed zinc deficiency symptoms and improved yields. Similar observations have been made in various areas throughout Nebraska. In addition, zinc deficiency of field beans has been noted in western Nebraska. Deficiency symptoms reported in the Great Plains states appear to be similar to the zinc deficiency symptoms described by Viets (1951) for corn and field beans in Washington.

E. Response of Non-legume Crops to Green Manures and Alfalfa in the Cropping System

Green manures have not benefited yields of non-legume crops on dryland soils in much of the Great Plains area (Hill, 1954; Brage, 1956; Westin *et al.*, 1955; Osenbrug and Mathews, 1951; Brandon and Mathews, 1944; Zook and Weakly, 1950; Kuska and Mathews, 1956; Locke and Mathews, 1953; Burnham and Leamer, 1954). Furthermore, alfalfa had no effect on yields of non-legume crops where it was included in the cropping system at the above locations. Green manures did increase the yields of some grain crops at a few locations (Conlon *et al.*, 1953; Brage *et al.*, 1954; Osborn and Mathews, 1955). However, the yield increases would hardly justify the practice in most cases. Substantial increases in yields of wheat and corn due to the inclusion of either sweet clover or alfalfa in the cropping system were reported by Haas (1955) for Mandan, North Dakota. He found a reasonably close relationship between grain yields in various cropping systems during the period from 1947 to 1953 and the loss of soil nitrogen during the forty years of cropping. It seems likely that the lack of crop response to green manures was associated with either the poor growth of the green manure crops or the reduction in soil moisture supply when they grew satisfactorily.

Including green manure crops and alfalfa in cropping systems on irrigated land are accepted practices in much of the Great Plains area. They aided materially in supplying non-legume crops with nitrogen, according to Fine (1956), Weakly and Nelson (1950), Rhoades and Harris (1954), Hill (1946), and Gardner and Robertson (1952).

F. Crop Response to Barnyard Manure

Grain yields generally have been increased more by the application of barnyard manure to dryland soils than by the use of green manures. Increased crop yields from the use of manure have been obtained at a number of locations (Conlon *et al.*, 1954; Haas, 1955; Brage, 1956; Locke and Mathews, 1953; Osborn and Mathews, 1955). However, no noticeable benefits in crop yield were obtained from the use of manure at other locations (Osenbrug and Mathews, 1951; Zook and Weakly, 1950; Kuska and Mathews, 1956; Burnham and Leamer, 1954).

Manure applications have been of decided benefit to irrigated crops (Harris, 1938; Nuckols, 1942; Hill, 1946; Weakly and Nelson, 1950). This favorable influence of manure may be attributed, in part at least, to phosphorus supplied in the manure.

G. Crop Response to Commercial Fertilizers

All states in the Great Plains have given considerable attention during the last ten years to evaluating the place of commercial fertilizers in crop production on irrigated and nonirrigated lands. Some of the many publications and reports which present crops response to fertilizer application will be referred to here.

1. *Row Crops*

In general, cotton and sorghums do not respond to applications of fertilizers on nonirrigated lands in the southern high Plains (Johnston, 1957). An exception was reported by Quinby and Fisher (1955) for a sandy soil near Chilicothe, Texas. Greb *et al.* (1954a) obtained increased yields of dryland corn and sorghum in eastern Colorado from the use of nitrogen fertilizer on sandy soils low in organic matter. They stressed the importance of an adequate soil moisture supply for obtaining responses of these crops to fertilizer application.

Substantial increases in yields of irrigated cotton and sorghum have been obtained from the use of nitrogen and phosphorus fertilizers (Johnston, 1957; Leamer, 1956). Irrigated corn (Gardner and Robertson, 1952; Rhoades *et al.*, 1954; Fine, 1956; and Pumphrey and Harris, 1956), sugar beets (Hill, 1946; Nelson *et al.*, 1948; Tolman *et al.*, 1948; Baird, 1952; Gardner and Robertson, 1952; Larson, 1952; Carlson and Herring, 1954; Rhoades and Harris, 1954; and Mellor *et al.*, 1956) and potatoes (Harrington, 1955) responded to applications of fertilizers. Nitrogen was the element needed most by corn but both nitrogen and phosphorus were needed by sugar beets and potatoes.

2. *Small Grains*

Small grains generally respond more than the row crops to applications of fertilizers on nonirrigated lands in the Great Plains. In general, the increases due to fertilizers have not been large and decreased yields have been reported. Small grains respond either to nitrogen or phosphorus fertilizer or to both (Norum *et al.*, 1957; Zubriski and Norum, 1955; Westin *et al.*, 1955; Olson and Rhoades, 1953; Greb *et al.*, 1954b; Locke and Mathews, 1953; Eck and Stewart, 1954; and Eck *et al.*, 1957).

Small grains respond to applications of fertilizers on irrigated lands (Gardner and Robertson, 1952; Mellor *et al.*, 1956). Response of irrigated wheat to nitrogen fertilizer depended upon the irrigation practice followed, according to Jensen (1956).

3. *Alfalfa and Grasses*

Variable responses have been obtained from the application of phosphate for alfalfa and legume-grass mixtures under irrigation (Peterson *et al.*, 1953; Leamer, 1956; Mellor *et al.*, 1956; Worzella *et al.*, 1953; and Lewis, 1955). A close relationship between soil test values for phosphorus and yield response were obtained by Mellor *et al.* (1956).

Harper (1957) reported increased yields of alfalfa on dryland soils in north central Oklahoma from applications of phosphate, lime, and manure. There was, however, a wide variation in yields of alfalfa by cuttings and by years because of differences in quantity and distribution of effective rainfall. Ehlers *et al.* (1952) reported increased yields of forage from native subirrigated meadows in the Nebraska sandhills from applications of nitrogen and phosphorus fertilizers. Phosphorus fertilizer was especially beneficial for establishing and maintaining legumes in these meadows.

McIlvain and Savage (1950) reported that 30 lb. of nitrogen per acre in 1947 and 53 lb. per acre in 1948 increased the grazing capacity of weeping lovegrass by 33 per cent and the gain of yearling steers by 37 per cent.

Increased seed production, yield, and crude protein content of forage were obtained by the application of nitrogen fertilizer to crested wheatgrass in the northern Great Plains (Norum *et al.*, 1957; Westin *et al.*, 1955; Stitt *et al.*, 1955). There was some response to phosphorus fertilizer at one location when high levels of nitrogen were applied (Stitt *et al.*, 1955).

Rogler and Lorenz (1957) at Mandan, North Dakota, reported substantial increases in yields of pasture forage from applications of 30 and 90 lb. of nitrogen per acre. They stated that "Two years of fertilization of a heavily grazed pasture at the 90-lb. rate of nitrogen did more to improve range condition and production than six years of complete isolation from grazing." Westin *et al.* (1955) questioned the continued use of fertilizers for native grass production in western South Dakota for economic reasons. Much more information is needed to determine the place of fertilizers in managing native grass pastures.

H. Factors Influencing the Response of Great Plains Crops to Nitrogen and Phosphorus Fertilizers

Marked variations in soil moisture supply during the growing season in both dryland and irrigated soils of the Great Plains should have an appreciable effect on crop response to fertilizers. In addition to the direct effect of soil moisture supply on plant growth, a differential effect of soil moisture supply on nutrient element intake can be expected (Richards and Wadleigh, 1952; Kelley and Haddock, 1954; Larson, 1954; and Jenne *et al.*, 1958). In general, the maintenance of a low soil moisture tension

during most of the growing season resulted in maximum responses of sugar beets (Haddock, 1953), sorghum (Painter and Leamer, 1953), and corn (Rhoades *et al.*, 1954) to applications of nitrogen fertilizer. Maximum increases in yields of dryland winter wheat and corn were obtained from the use of nitrogen fertilizer where the soil was at field capacity wetness to a depth of 6 feet or more at planting time (Ramig and Koehler, 1955, 1957). The latter studies indicate that stored water is highly important in determining the response of dryland crops to nitrogen fertilizers.

Most studies in the Great Plains states indicate that the common nitrogen carriers are equally effective in supplying fertilizer nitrogen, when applied properly (Eck *et al.*, 1957; Greb *et al.*, 1954a,b; Olson and Rhoades, 1953; Rhoades *et al.*, 1954). Time of application for the most efficient utilization of fertilizer nitrogen varied somewhat with the carrier. Finney *et al.* (1957) pointed out that urea could be used effectively during the fruiting period as a spray application to increase protein content of the grain.

Considerable attention has been given to the study of different phosphate carriers for supplying fertilizer phosphorus to various crops. Degree of water solubility as a factor in availabilty to varous crops grown on calcareous soils has received special attention (Olsen *et al.*, 1950; Rogers, 1951; Tisdale and Winters, 1953; Bennett *et al.*, 1954; Brenes, 1955; Schmehl *et al.*, 1955; and Olson *et al.*, 1956a). These studies indicate that the superphosphates and ammonium phosphates are either superior or equal to all other phosphorus carriers in supplying fertilizer phosphorus to crops grown on calcareous soils. Furthermore, such carriers as colloidal phosphate, rock phosphate, and tricalcium phosphate are considered to be ineffective for use on calcareous soils. However, marked differences in results have been reported for the use of calcium metaphosphate and Rhenanian-type phosphates on calcareous soils. These carriers have been nearly as effective as superphosphate on calcareous soils in Colorado, especially when finely ground and thoroughly mixed with the soil (Brenes *et al.*, 1955; Schmehl *et al.*, 1955). They have been decidedly less effective than superphosphate when applied to other calcareous soils according to Olson *et al.* (1956a) and Tisdale and Winters (1953). Nitric phosphates may be as effective as superphosphate on calcareous soils, according to Schmehl *et al.* (1955). Olson *et al.* (1956a) found that a 17-22-0 nitric phosphate of quite low water solubility was much less effective than superphosphate on calcareous soils, whereas a 12-33-0 nitric phosphate of higher water solubility was nearly as effective as superphosphate. It seems evident that more information is needed before general recommendations can be made regarding the use of calcium metaphosphate, Rhenanian-type phosphates, and nitric phosphates on calcareous soils.

There is a considerable body of evidence to indicate that nitrogen placed in association with phosphate fertilizer greatly enhances the proportion of fertilizer phosphorus used by plants. Similar results have been experienced in the Great Plains states (Fine, 1955; Olson and Dreier, 1956; Olson *et al.*, 1956b). These results indicate that the ammonium ion has a greater influence than the nitrate ion on the utilization of fertilizer phosphorus by plants.

I. Use of Fertilizers in the Great Plains States

Fertilizer usage has increased markedly in the Great Plains states. For example, there was 10.4 times as much fertilizer nitrogen, 3.4 times as much fertilizer phosphorus, and 3.5 times as much fertilizer potassium used in the Great Plains states in 1954 as in 1945.[1] During 1954 fertilizer usage in the U.S. compared with 1945 was 2.8 times as much for fertilizer nitrogen, 1.5 times as much for fertilizer phosphorus, and 2.9 times as much for fertilizer potassium. It seems reasonable to assume that much of the increased use of fertilizers on irrigated land in the Great Plains states was within the Great Plains portions of those states. In contrast, it seems likely that the greatest proportion of the increased use of fertilizers on nonirrigated land was confined to the more humid portions of Texas, Oklahoma, Kansas, Nebraska, South Dakota, and North Dakota.

J. Research Needs

It is evident that soil fertility problems exist in the Great Plains. Furthermore, it seems likely that some of the present problems will become more acute and other problems will develop with a further decline in soil fertility levels. A major breakthrough in our knowledge of controlling soil water losses in the vapor state would make additional water available for crop production. It would also result in greater crop responses to applications of fertilizers supplying deficient nutrient elements.

Further research is needed to evaluate the interrelationships of the various environmental factors which influence crop response to fertilizer application. Soil moisture supply present or expected at planting time is now being used in addition to the common soil tests for making recommendations for fertilizer use. However, the information available at present is not adequate for making precise recommendations for all crops under the varied soil and climatic conditions of the Great Plains. The importance of using other environmental factors in evaluating fertilizer response also needs investigation.

Research on methods of testing soils for nutrient element deficiencies

[1] Calculated from information in "Agricultural Statistics, 1947." U.S. Dept. Agr., Washington, D.C., 1948; and *U.S. Dept. Agr. Statist. Bull.* **216**, 1957.

should continue. Reasonably good methods exist for testing phosphorus and potassium deficiencies and lime needs. However, there is a need for an improved method of evaluating soil nitrogen. Methods for testing other nutrient elements including the minor elements should be developed for Great Plains soils.

More information is needed on the nutrient element status of grassland soils. The role of fertilizers for improving and maintaining meadows and pastures should be further evaluated for the different kinds of sites existing in the Great Plains.

VI. Irrigation

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Early development of irrigation began principally in the drier, western regions of the Great Plains. Irrigation projects were confined primarily to river bottom lands where flow from rivers could be easily diverted for crop use. More recently, irrigation has been expanded to upland soils in the higher rainfall areas where water supplies are available or can be developed. This has brought about a number of soil and water management problems peculiar to an area where rainfall has at times been inadequate to support a dryland agricultural economy.

A. Trends in Irrigated Acreage and Proportion of Crop Value

The trend of irrigation development in the Great Plains states between 1949 and 1954 is indicated in Table IV. North and South Dakota show only a small increase in irrigated acreage but more than 2 million acres of land are considered potentially irrigable in these states by diverting water from the Missouri River. In contrast, a marked increase in irrigated acreage occurred in Nebraska, Kansas, Oklahoma, and Texas, primarily as a result of the 1950–1956 drought in the central and southern High Plains. Irrigation water shortages in Wyoming, Colorado, and New Mexico resulted in temporary retirement of some land from production.

The per cent of crop value from irrigated land in 1954 (Table IV) reflects the relative importance of irrigation to the agricultural economy of the states. The per cent of crop value ranges from less than 1 per cent in the Dakotas to 85 per cent in New Mexico. Although Montana shows irrigated crop values at 20 per cent in 1954, Thompson *et al.* (1956) found that in the drought years from 1930 to 1938, from 34 to 63 per cent of the crop value came from irrigated lands. During this period only 18 to 29 per cent of the total crop acreage was under irrigation. These figures em-

TABLE IV

Irrigated Acreages in 1949 and 1954, Total and Irrigated Crop Values, and Per Cent Crop Value from Irrigated Land in Great Plains States[a]

State	Irrigated acreage 1949	Irrigated acreage 1954	Crop value, 1954 (in thousands) Total	Crop value, 1954 (in thousands) Irrigated	Per cent crop value from irrigated land 1954
North Dakota	35,294	37,672	$ 447,120	$ 1,369	0.3
South Dakota	78,069	90,371	416,840	2,668	0 6
Nebraska	876,259	1,171,369	656,420	55,707	8 0
Kansas	138,686	331,551	651,868	9,170	1 4
Oklahoma	34,071	108,151	306,310	14,706	4.8
Texas	3,131,534	4,707,028	1,304,721	522,627	40 0
Montana	1,716,792	1,890,671	278,669	56,698	20.0
Wyoming	1,431,767	1,262,632	58,242	38,698	66 0
Colorado	2,872,348	2,262,921	200,319	122,456	61 0
New Mexico	655,287	649,615	99,250	84,091	85.0

[a] Irrigated acreages and production figures obtained from "1954 Census of Agriculture," Vol. I. U.S. Dept. Commerce, Bur. of the Census, Washington, D.C.; and crop prices from "Agricultural Statistics, 1955." U.S. Dept. Agr., Washington, D.C.

phasize the importance of irrigation in stabilizing agricultural production during periods of subnormal rainfall.

B. Comparative Yields of Dryland and Irrigated Crops in the Great Plains

Benefits derived from irrigating crops in arid regions are self-evident. In the subhumid climate of the Great Plains, a dryland agricultural economy has developed under limited rainfall conditions. When irrigation water is applied to crops in addition to rainfall received, yields are almost always increased. Whether or not the increase in production warrants conversion from a dryland to irrigated agriculture is a matter for consideration by both the economist and the farmer.

Data compiled in Table V, although not strictly comparable in all cases, give some indication of the relative magnitude of dryland and irrigated crop yields. Many of the locations reported are in the higher rainfall areas of the Great Plains; hence, the percentage increases from irrigation are not as great as would be expected in the more arid regions. Also, in certain cases, the data represent only one year's results, as at Lincoln and North Platte, Nebraska, in 1956. However, these data emphasize the

TABLE V

Average Annual Yield of Dryland vs. Irrigated Crops Produced at Various Locations in the Great Plains for Year(s) Indicated

Crop and location	Dry land Year(s)	Dry land Yield (bu.)	Irrigated Year(s)	Irrigated Yield (bu.)	Per cent increase
WHEAT					
Huntley, Montana (Spring)	1913–53	13.6	1929–37	53.0	290
Garden City, Kansas (Winter)		13.6		55.0	304
Redfield, South Dakota (Spring)	1949–53	25.6	1949–53	33.9	32
Bushland, Texas (Winter)	1942–56	8.9	1956	52.4	489
BARLEY					
Huntley, Montana	1913–53	11.7	1938–53	78.0	566
Newell, South Dakota	1909–55	21.1		49.0	132
Redfield, South Dakota	1949–53	28.0	1939–43	38.6	38
Mandan, North Dakota	1915–53	21.9	1951–52	53.0	142
CORN					
Huntley, Montana	1913–53	14.4	1929–53	78.0	442
Lincoln, Nebraska	1956	3.0	1956	77.0	2466
Redfield, South Dakota	1949–53	42.2	1949–53	90.5	114
Upham, North Dakota	1956	31.3	1956	66.9	114
Newell, South Dakota	1909–55	24.7		52.0	110
Mandan, North Dakota	1915–53	26.1	1952	85.5	228
North Platte, Nebraska	1956	20 0	1956	140.0	600
OATS					
Huntley, Montana	1913–53	29.4	1929–53	106.0	260
Newell, South Dakota	1909–55	26.7		66.0	147
Redfield, South Dakota	1949–53	37.6	1949–53	58.0	54
Mandan, North Dakota	1915–53	37 2	1951–52	91.0	145
GRAIN SORGHUM					
Garden City, Kansas	—	29.5	—	90.0	205
Bushland, Texas	1942–56	14.9	1956	113.0	658
FLAX					
Huntley, Montana	1913–51	6.9	1912–36	24.0	248
Newell, South Dakota	1909–55	6.5		14.0	115
ALFALFA					
Redfield, South Dakota	1950–53	2.71 T.	1950–53	5.05 T.	86
Newell, South Dakota	1909–55	0.80 T.		4.60 T.	475
ALFALFA-BROME					
Huron, South Dakota	1950–52	2.0 T.	1949–51	3.52 T.	76
Upham, South Dakota (pasture)	1955–56	1.08 T.	1955–56	2.25 T.	108
(hay)	1955–56	1.55 T.	1955–56	3.51 T.	126
POTATOES					
Mandan, North Dakota	1915–53	133.0	1951–52	448.0	236

benefits of irrigating corn in a year when dryland production was almost a failure because of drought. Results at Lincoln were obtained with one "off-season" irrigation in contrast to a pre-irrigation plus three subsequent irrigations at North Platte. The relatively low percentage increase of irrigated spring wheat at Redfield, South Dakota, supports results obtained at Upham, North Dakota. Spring wheat grown with adequate fertility and irrigation seldom yielded more than 40 bushels per acre. Factors limiting spring wheat growth under irrigation in this area of the Great Plains are not fully understood.

C. Irrigation Water Supply

Dependable surface water supplies originating from mountain snowmelt in New Mexico, Colorado, and Wyoming have for some time been appropriated and in many instances overappropriated for domestic, irrigation and industrial use. During the past five or six years of drought, shortages of water for irrigation purposes resulted in the temporary retirement of some irrigated land from production. Transmountain diversion of water from the west slope to the east slope under the Big Thompson Reclamation Project in Colorado partially relieved existing critical water shortages for irrigation in some areas.

The Missouri River Basin Development Project authorized by Congress under the Flood Control Act of 1944 is providing surface storage of water for various uses including irrigation in the eastern portion of the Great Plains. When completed, there will be more than 100 multi-purpose reservoirs on the Missouri River and its tributaries with a combined capacity of 110 million acre feet of water. Sufficient water supply for irrigation purposes will be available to irrigate more than the 5 million acres of land proposed for development and to supplement the 2 million acres now receiving inadequate supplies.

Use of underground water supplies where available has expanded rapidly during the 1950–1956 drought. Most of the water is being pumped from the Ogallala formation extending from the Black Hills of South Dakota to the southern part of the Texas Panhandle and including parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas. However, prospects of a permanent irrigated agriculture dependent on pump irrigation in parts of the southern High Plains appears questionable in view of present ground water supplies. In the period 1950–1957, the number of wells in the Texas High Plains had increased from about 14,000 to 42,000. The High Plains Underground Water Conservation District No. 1 in Lubbock, Texas, estimated the available supply at 102 million acre feet in 1938. Approximately 18 per cent of this amount already has been used. The natural recharge rate to the under-

ground reservoir is about 30,000 acre feet annually. With a potential use of 3 to 4 million acre feet annually, it would appear that present water supplies will last about twenty to twenty-five years. Beene (1957), reporting on the water situation in southwestern New Mexico, has indicated that ground water supplies in that area will be depleted in fifteen years.

At present, the possibilities of utilizing recharge wells for conveying runoff water that accumulates in wet-weather lakes to underground storage are being investigated. Broadhurst and Willis (1955) reported results of one well installation after 8 days of operation. In this period of time, 4,200,000 gallons of water or 13 acre feet were stored for future irrigation use. The intake rate of the well gradually decreased from an initial 1,050 gallons per minute to a rate of 200 gallons per minute at the end of the period.

In Nebraska, Greenshields (1955) states that the rapid development of well irrigation has been possible because of good ground water supplies in relatively shallow, water-bearing materials. Over-development appears unlikely in most areas of the state because sufficient reserves are available to handle drier periods when depletion rates exceed recharge rates. In 1953, Nebraska farmers were pumping 9,718 wells that irrigated 588,000 acres of land. An estimated 1,000 additional wells were drilled in 1954.

Pfister (1955) indicated that in 1953, southwestern Kansas had approximately 160,000 acres under irrigation. Approximately 1,500,000 acres could be developed with present water supplies. The water situation in this area is similar to Texas in that recharge of underground supplies will be only a fraction of that pumped when available irrigated acreages are developed fully. The number of acres irrigated from wells in 1949 totaled 83,924 compared to 1,569 acres in 1909. The 1949 figure represented 60 per cent of the total irrigated acreage at that time.

D. Method of Irrigation

Irrigation efficiencies in older irrigated projects of the West seldom exceed 50 per cent. This means that more than half of the water diverted from rivers and reservoirs is lost in conveyance, runoff, or deep percolation. Most of the irrigation methods adapted to the arid West are being used in the Great Plains.

Surface irrigation in contrast to sprinkler and subirrigation methods predominates in most states. With the serious limitation of water supplies in the southern High Plains, some farmers have adopted level border irrigation systems such as shown in Fig. 6. Some advantages of level irrigation systems are high application and distribution efficiencies, uniform water distribution, reduced labor costs, elimination of runoff from rainfall or

irrigation, leaching for salinity control, and reduction of use of excess i gation water that contributes to the drainage problem.

Level irrigation is adopted to most crops that can be irrigated by graded border or furrow irrigation method. Slopes up to 6 per cent h been benched satisfactorily for level irrigation on deep soils, but method cannot be used on shallow soils where cuts expose subsurf gravel or bedrock. Relatively large streams of water, usually from 2 t cubic feet per second, are required for good distribution of water. Des criteria for level systems of irrigation have been developed and descrit (Swanson and Ross, 1957).

FIG. 6. Sorghum production on level contour, bench irrigation system in the T high Plains.

Level and graded bench systems of irrigation currently are being stalled in the Platte and Republican River projects of Nebraska. Althou some level systems have been installed, some authorities feel that so grade is needed for surface drainage in wet seasons to allow for cultivat of row crops and for the orderly disposal of excess water from high int sity storms. At present, the amount of grade required for such system not known.

Flooding downslope from contour ditches where topography is un lating is a common but inefficient irrigation method practiced in so areas. Siphons and gated-pipe, popular with many farmers where r crops are irrigated, provide for more efficient irrigation and control water.

Sprinkler irrigation systems are being used to irrigate many of crops grown under irrigation in the Plains area, including corn. The m

common type in use is portable, quick-coupling, aluminum pipe with rotating head or circular spray nozzles. At present, the irrigated acreage under sprinkler is about 184,000 in Oklahoma, 30,500 in North Dakota, and 363,980 in Texas. This represents about two-thirds, one-half, and one-twelfth of the total irrigated acreage in each state.

Some subirrigation is being used to grow alfalfa in the Platte River valley of Nebraska and elsewhere in the Plains. However, this method of irrigation is limited to those conditions where an artificial water table can be created and maintained at a predetermined depth below the surface within reach of plant roots. In some areas, the number of surface irrigation applications can be reduced when roots of perennial crops such as alfalfa reach the capillary fringe above the water table. Unpublished data of R. E. Campbell, Huntley, Montana, has shown that established alfalfa grown in the presence of a fluctuating water table (5–9 feet) produced 20.2, 21.0, 21.3, and 21.9 tons of hay per acre in a four-year period, 1953–1956, with no irrigation, one irrigation early in season, one irrigation per cutting, and two irrigations per cutting, respectively. Similar results were obtained at Mandan, North Dakota.

E. Soils Problems Associated with Land Leveling

Surface soils in the Plains area contain most of the essential nutrients needed for plant growth and organic matter needed for good tillage. When soils are prepared for surface irrigation, a portion or sometimes all of the surface layer may be removed in the leveling process. Restoring the productivity of exposed subsoils where excessive cuts are necessary sometimes requires special soil management practices. Often these denuded areas occupy only a small portion of the field and can be treated separately.

In general, removal of surface soil creates nutritional problems including phosphorus, nitrogen, zinc, and iron deficiency on sensitive crops such as beans and small grains.

Whitney *et al.* (1948, 1950) found that both manure and commercial fertilizers were effective in producing practically normal yields of corn, sugar beets, and spring wheat on exposed subsoil in a very short time. Rates of N, P, and K were equal to the total amount contained in 27 tons of manure. After the first year, subsoil plots exhibited a very favorable structure which facilitated an excellent stand of sugar beets. Yields of sugar beets on check plots averaged about 8 tons per acre, compared to 18.6 tons on plots receiving both nitrogen and phosphorus.

Unpublished data of Grunes and Carlson (USDA) working at Upham, North Dakota, have shown that corn grown on leveled Gardena subsoil without nitrogen and phosphorus additions was zinc deficient. Additions of 180 lb. of nitrogen and 100 lb. of P_2O_5 with and without 15 lb. of zinc

sulfate an acre, increased corn forage yields 5,390 to 6,420 lb., respectively. When no fertilizers were added, yields were 1,480 lb. an acre, compared to 7,940 lb. when the above rates of nitrogen, phosphorus and zinc, and 20 tons of manure were used.

The per cent of surface soil required to supply adequate phosphorus when mixed with C_1 horizon subsoil material was investigated by Carlson and Grunes (1958). They found that at least 25 per cent of surface soil mixed with the subsoil was required to supply sufficient available phosphorus for good growth when nitrogen was not limiting. These results point out the desirability of leaving in place as much surface soil as economically possible in the leveling process.

Rainfall often interferes with leveling operations. Heavy leveling equipment used on wet, finer textured soil can create undesirable physical conditions not easily remedied. The most favorable time for leveling usually occurs in the fall, particularly in the eastern portion of the Plains area.

F. Consumptive Use

Design of both project and farmstead irrigation systems requires knowledge of seasonal and peak consumptive use rates. Measured consumptive use data compiled from various locations for the principal irrigated crops grown in the Great Plains area are tabulated in Table VI. Seasonal consumptive use includes the amount or depth of water transpired by the crop in addition to that lost by evaporation from the soil surface. Peak use rate per day represents the highest average daily use of water in inches for a given interval of time, usually 7 to 15 days.

Inches of water required to produce a given crop in most instances varies within relatively narrow limits for different locations. One notable exception was small grains grown at Redfield, South Dakota, and Bushland, Texas. The latter location required about 12 additional inches of water to produce a crop of winter wheat than was required for spring wheat in South Dakota. However, the consumptive use period at Bushland, Texas, including the winter months, was more than twice the duration of that at Redfield, South Dakota. In general, alfalfa requires about the same amount of water as sugar beets (approximately 24 inches); potatoes about the same amount as corn (approximately 18 inches); and small grain about the same amount as dry beans (approximately 16 inches). Differences in net radiation, humidity, wind movement, length of growing season, etc., at the various locations account for much of the variability in consumptive use values obtained.

Daily peak use rates (Table VI) for the various crops were not available for all locations. At Upham, North Dakota, the range in daily peak use rates for the three- or four-year study are shown. Rates varied in dif-

TABLE VI

Measured Seasonal Consumptive Use, Net Irrigation Requirements, and Peak Daily Use Rate of Principal Crop Compiled from Various Locations in the Great Plains

Crop, location, and year	Measured seasonal consumptive use (inches)	Seasonal precipitation (inches)	Average net irrigation requirement for period (inches)	Long time average seasonal precipitation (inches)	Peak use rate per day (inches)	Average consumptive use period (days)
Alfalfa						
Upham, North Dakota[a] (1954–56)	23.4	10 1	13 3	10.8	0 26–0 39	143
Redfield, South Dakota[b] (1950–53)	22 2	13 2	9 0	14.4[c]		124
Scottsbluff, Nebraska[d] (1932–36)	25 9			12 4[c]		166
Arapahoe, Nebraska[d] (1950)	26.2	-	--	-	-	—
Sugar Beets						
Huntley, Montana[e] (1953)	22.5	6 5	18 0	8 7	0 23	160
Redfield, South Dakota[b] (1951–53)	24 0	12 1	11 9	14.4	-	--
Scottsbluff, Nebraska[d] (1932–36)	24.0			12.4[c]		-
Potatoes						
Upham, North Dakota[a] (1953–56)	18.4	9 2	9 2	10.8	0.27-0 37	112
Redfield, South Dakota[b] (1950–53)	15 5	11.5	4 0	14.4[c]	—	--
Scottsbluff, Nebraska[d] (1935)	15.4	--	—	12.4[c]	--	—
Mandan, North Dakota[f] (1953)	17.9	13.4	4.5	10.9	0.36	128
Corn						
Upham, North Dakota[a] (1953–56)	17 5	8 6	8.9	10.8	0 20–0 36	107
Redfield, South Dakota[b] (1951–53)	16 6	10 8	5 8	14.4[c]	--	—
Hot Springs, South Dakota[g] (1955)	21.1	10.1	11.0	13 8[c]	--	124
Grain Sorghum						
Bushland, Texas[h] (1955)	21 9	5 4	16 3	8.4	0.34	121
Small Grain						
Upham, North Dakota[a] (1954–56)	15.9	8.0	7.9	10.8	0.25-0.38	98
Redfield, South Dakota[b] (1953)	16.3	—	—	14.4[c]	—	--
* Bushland, Texas[h] (1955–56)	28.0	7 9	20.1	7.2	0.31	222
Dry Beans						
Redfield, South Dakota[b] (1952–53)	16 4	-	—	14.4[c]	--	—
Hot Springs, South Dakota[g] (1956)	13.2	4.4	8 8	—	—	92

[a] Unpublished data obtained cooperatively between North Dakota Agr. Expt. Sta., Fargo, North Dakota, and Agr. Research Serv. Mandan, North Dakota (1954-56)
[b] Erie and Dimick (1954)
[c] Climate and Man. *Yearbook Agr , U.S Dept. Agr.* 1941.
[d] Monson (1953).
[e] Larson and Johnston (1955).
[f] Unpublished data, H. R. Haise, Agr. Research Serv., formerly at U.S. Field Sta., Mandan, North Dakota (1953).
[g] Unpublished data, N. A. Dimick and W. R. Zich. Obtained cooperatively between South Dakota Agr. Expt. Sta., Brookings, South Dakota, and Agr. Research Serv. (1955-56).
[h] Unpublished data, M. E. Jensen and W. H. Sletten, Agr. Research Serv., Bushland, Texas.
* Winter wheat.

ferent years as much as 0.16 inch per day for corn, 0.13 inch per day for small grain and alfalfa, and 0.10 inch per day for potatoes. These differences are primarily the result of a relatively wet, cool growing season compared to a hot, dry season. It is noteworthy that the peak use rate for small grain was as high as that for alfalfa.

Peak use rates for most crops occur during the stage of most rapid vegetative growth and usually include the fruiting period. This period of plant development also corresponds to the time when, during June, July, and August, the climate reaches its maximum evaporative potential. Jensen and Sletten, 1957, found that the maximum water use rate for grain sorghum at Bushland, Texas, occurred in August, 1954, during the fruiting period. Erie and Dimick (1954) reported peak use rates for flax about 10 days after blossom; sugar beets in the middle of growing season; potatoes at the time tubers set; corn shortly after the silking stage, dry beans at blossom; and wheat during the early boot stage.

G. Research Problems

Expansion of irrigation in the Great Plains has created special research problems in addition to those common to arid regions. Some of the more important ones include the following:

1. Water inventories of both surface and underground supplies, the interrelationships of each, and the rate of natural recharge of underground reservoirs.
2. Basic long-term yield data for both irrigated and dryland production including studies on drought probabilities, particularly in the subhumid areas, for computing cost-benefit ratios as a result of irrigation.
3. Efficient use of water including methods of irrigation, choice of crop, and how to use limited amounts of water, either extensively or intensively.
4. Methods for recharging underground aquifiers, particularly in areas where surface runoff accumulates in wet-weather lakes.

VII. Wind Erosion Problems

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The wind erosion problem, just as most agricultural problems in many parts of the world, developed after man began to interfere unduly with the natural equilibrium between vegetation, soil, and climatic environment. Overcultivation, burning, and overgrazing have been his chief means

of disturbing this equilibrium. The problem, therefore, is associated with the way the farmer uses his land.

A. Present Situation and Practices

The driest sections of the Great Plains generally are most seriously affected by wind erosion. Crops often have been destroyed by abrasive action of windblown soil particles. These losses, though serious, are less important than loss of silt, clay, and organic matter gradually sorted from the surface soil and carried to distant areas where they may be of little or no use to agriculture (Daniel, 1936; Chepil, 1957a). Crop yields in some areas have been much lower after than before serious erosion by wind occurred (Finnell, 1949). In some cases, the land appears to have been injured permanently.

The primary causes of wind erosion are few and can be stated simply. Wherever (1) the soil is loose, finely divided, and dry, (2) the soil surface is smooth and bare, and (3) the wind is strong, erosion may be expected.

By the same token, wherever (a) the soil is compacted, kept moist, or made up of stable aggregates or clods large enough to resist the force of wind, (b) the soil surface is roughened or covered by vegetation or vegetative residue, or (c) the wind velocity near the ground is somehow reduced, erosion may be curtailed or eliminated. These general conditions form the basis for effective wind erosion control.

The most important of the major causes of wind erosion appears to be the depletion or destruction of vegetation or vegetative residue on the land. Drought at times has reduced or stopped the vegetative growth, but drought alone has not been the cause of serious wind erosion. Little erosion occurred when the land was protected by natural vegetation. Vegetative cover is nature's way of protecting the earth's surface from erosion. Man has not been able to devise a more effective practical way to control erosion. Adequate protection of the land by vegetation or vegetative residue still remains the key to both wind and water erosion control.

Extended periods of drought and high wind velocity have contributed to the severity of wind erosion. Great variations in precipitation, temperature, and wind velocity exist on the Plains. These variations are governed by certain probability laws. Therefore, the general frequency of occurrence of periods of high wind and precipitation are predictable from past records for any location (Zingg, 1949). Unfortunately the time when these periods will occur cannot be predicted. It is essential, therefore, to establish permanent soil conservation practices that will be effective against wind erosion whenever adverse climatic conditions occur.

The growing of cultivated crops incapable of providing sufficient vege-

tative cover on the land has contributed greatly to land denudation and erosion by wind. Cotton, sugar beets, peas, beans, and potatoes, leave little cover on the land and contribute greatly to erosion of soil by both wind and water. Some land classes require less cover than others for protection against erosion and are therefore more suited to those erosion-susceptible crops, especially if special farming systems such as strip cropping and rotation with erosion-resistant crops are adopted. Some land classes, on the other hand, require the adoption only of erosion-resistant crops and some permit no cultivated crops if erosion is to be controlled. In this country, large areas of land suited only for permanent grass or forest cover are still devoted to cultivated crops. In the Great Plains alone about 14 million acres not suited for permanent cultivation were cultivated in 1955.[1] Much of this land offers meager returns and is subject to severe wind erosion even in average years.

Another cause of depletion of a vegetative cover and consequent erosion by wind has been the improper choice and use of tillage implements. In the early period of agricultural history in this country, the plow and the disk and drag harrows developed in and adapted to more humid areas were the principal tillage implements in dry regions. Vegetative residues were buried and the soil was often left smooth, loose, and fine and thus highly erodible by wind. Later, when the importance of vegetative cover began to be recognized, the plow in many cases was discarded and the one-way disk which leaves some residue on the surface, was adopted. With careful use, the implement served and is still serving a good purpose. However, improper or excessive use of this implement has often resulted in the soil surface becoming loose and fine with much of the residue buried.

The practice of fallowing, essential for storage of soil moisture in dry regions, often has created large areas of bare or partially denuded land. In the northern sections, the fallowed land is seeded in spring about 20 months after harvesting a previous crop. During all this period the ground must be kept free from weed growth if moisture is to be conserved. Tillage so far has been the only practical means of killing the weeds. This tillage tends to break up and bury the vegetative residue needed for protection of the surface against erosion by wind and water. Consequently, great care is required if weeds are to be killed, moisture conserved, and erosion curtailed. Due to lack of better methods, a farmer often has to compromise by curtailing tillage and losing some soil moisture to gain a possible decrease in erosion, or vice versa.

In the southern sections fallow is sown, usually to wheat, in the fall. If germination and growth are favorable, a good protective cover against next spring's winds is almost assured. If the surface soil is dry, however,

[1] *U.S. Dept. Agr. Leaflet* SCS 394, 1955.

and wheat fails to germinate or make sufficient growth, the danger of wind erosion becomes acute. Some lands have been so highly susceptible to wind erosion that fallowing had to be abandoned in preference to a continuous system of cropping. Continuous cropping increases the hazard of crop failure but on the other hand assures a more continuous vegetative cover and reduced erosion. Where fallowing was attempted and wind erosion resulted, drastic emergency tillage measures had to be utilized to check the spread of erosion to other lands.

Another conflict often is encountered in the date of seeding winter wheat. Better protective cover against erosion may be expected with an earlier date of seeding. However, too early seeding induces the development of certain insects and diseases and uses valuable stored water which often reduces yields. Some insects may be controlled by burying the crop residue, but this practice undoubtedly induces erosion. Also, some weeds can be controlled best by plowing the weed seeds under, but such a practice also increases the hazard from erosion.

The wind erosion problem is complicated because it is dependent on many conditions and because it is interrelated with many other technical and economic problems. Each condition can be modified considerably by human action. A thorough understanding of the physics of the wind erosion process and the principles of soil stabilization are prerequisites for its solution.

B. Recent Developments

Probably one of the greatest advances in wind erosion control in recent years has been the retention of crop residues (stubble mulch) at the surface of the ground. Although the beneficial value of stubble mulch as a preventive measure against wind erosion was recognized in some areas more than thirty years ago, little basic information was available and its general adoption has been slow. Gradually, its value for wind erosion control was recognized from many investigations, some examples of which are cited in this article (Bennett, 1939; Duley and Russel, 1948; Hopkins *et al.*, 1946).

Maintenance of crop residues on cultivated land has been facilitated by considerable progress made in development, improvement, and application of tillage implements that tend to leave the crop residues on the surface of the ground (Chase, 1942; Duley and Russel, 1942; Johnson, 1950). During wind erosion conditions of the 1950's, farmers in many parts of the Plains have been able to control wind erosion by resorting to emergency tillage. Success of emergency tillage appears to be largely due to recent improvements in emergency tillage machinery and more adequate power for proper adjustment of speed and depth of cultivation.

Intermediate to moderately high speeds of 3.5 to 5 m.p.h. have produced the greatest degree of cloddiness and surface roughness and reduced the erodibility more than slower speeds if tillage was performed at a depth sufficient to bring up clods (Woodruff and Chepil, 1956).

Measurements have indicated that rate of soil movement by wind is zero on the windward edge of an eroding field, but increases with distance to leeward in some cases for more than a mile (Chepil and Milne, 1941). This increase in rate of soil flow with distance downwind across an unsheltered wind-eroding area is known as avalanching. The rate of soil avalanching has an important bearing on how wide erosion-susceptible strips in a strip cropping system should be to give a certain degree of erosion control. The more erodible the soil, the narrower the strips must be for equal effectiveness. Soil erodibility was found to be associated closely with soil textural class (Chepil, 1953). Recent work indicates how wide erosion-susceptible strips should be for any soil textural class, height of wind barrier in the erosion-resistant strips, wind velocity, and wind direction, to hold soil loss to a tolerable rate on the leeward sides of strips (Chepil, 1957b). Suitable width of strips is based on the tolerable rate of erosion. This width assumes the quantity of crop residue, degree of surface roughness and/or soil cloddiness that can be expected with proper farming practices in years of limited precipitation, high wind velocity, and low crop yields. The system, even then, will fail on rare occasions.

Researches have shown that strip cropping alone is not sufficient as a wind erosion control measure under most circumstances. It must be supplemented with other practices. Strip cropping can be expected to reduce the intensity of erosion and to limit the erosion to the area of origin. Without strip farming, once erosion starts it generally gets out of control. With strip farming, on the other hand, erosion is much more easily held in check, provided an effective set of erosion resistant strips is maintained.

A method of estimating wind erodibility of farm fields and of determining land surface conditions required to reduce wind erodibility to any degree was developed by Chepil and Woodruff (1954). The method is based on three major factors that influence wind erodibility of a field surface. They are surface roughness, vegetative cover, and degree of soil cloddiness. The method indicates how these factors can be measured, how erodibility of a field surface can be determined, and what degree of surface roughness, vegetative cover, and soil cloddiness would be needed to reduce erodibility to any degree.

Considerable fundamental information has been obtained recently on the value of shelterbelts, hedges, snow fences, and other barriers for wind erosion control (Woodruff, 1954). The work indicated that complete protection from wind erosion of dune sand occurs within a net distance of 9

barrier heights from a single row belt for a velocity of 40 m.p.h. at 50-foot height. This information gives some idea of barrier spacing required for full protection of highly erodible soil.

Some information on probabilities of occurrence of various levels of wind velocity, temperature, and precipitation associated with dust storms have been reported by Zingg (1949). This study points the way to determining how often certain degrees of drought and wind erosion conditions will occur at any given geographic location on the Great Plains.

Results obtained primarily with wind tunnels have indicated that the most erodible soil fractions are about 0.1 millimeter and the least erodible seldom exceed 1 millimeter in equivalent diameter (Chepil, 1951). These particles or grains are moved along the surface of the ground in jumps known as saltation. Saltation is the cause of two other types of movement —rolling and sliding along the surface (surface creep), and lifting of fine dust in the air (suspension). Saltation is a predominant type of movement on arable soils. Because of this movement, it is evident that erosion is dependent primarily on the velocity and force of the wind. Therefore one of the principles of wind erosion control should be based on preventing soil from becoming finely granulated, a condition most inducive to movement by saltation.

C. Research Problems

It is known at present what soil structure approaches an ideal condition for resisting wind. Attempts to achieve such a condition have met with little success. Creation of soil structure that would resist erosion, absorb water freely, and maintain a good medium for crop growth is urgently needed at the present time.

Although considerable information on the value of crop residues has been obtained, little is known of the influence of kind, manner of placement, and degree of anchorage of various types of crop residue on wind erodibility of different soils under various wind velocities. So far, only the influence of amount of crop residue has been investigated in detail.

A study of the effects of soil compaction, texture, and moisture on different types of tillage action is needed for development of more effective wind erosion control by tillage methods. An implement that leaves the soil surface in a cloddy condition without burying the crop residue is required.

Analyses of air flow, temperature, and evaporation patterns over and around shelterbelts and other types of surface barriers such as snow-fences, hedges, crop strips, ridges, and soil aggregates are being continued. Part of this study is to be applied to a classification standard for shelterbelts presently in existence on the Plains. Ultimately it is hoped that some clari-

fication may be made of the principles governing air flow patterns and soil erodibility in the vicinity of all barriers ranging from the size of clods to field shelterbelts.

Measurements of aerodynamic forces on soil particles on the ground and at different heights in a fluid boundary are being continued. These measurements include determination of the magnitude of fluctuation in aerodynamic forces at various heights above surfaces of various degrees of roughness. The measurements also include determination of the equilibrium conditions between the transported soil particles and the moving fluid. These studies are basic to an understanding of the physics of soil movement by wind and of the principles of wind erosion control.

Study of climatic factors influencing wind erosion on the Great Plains has been initiated but little information is available at present on the probabilities of occurrence of various intensities of wind erosion conditions for different soils and geographic locations. Many wind erosion control practices stand or fall depending largely on whether or not they can survive certain intensities of wind erosion. A study is needed for different soils and geographic locations on the quantity of crop residues and degree of surface roughness and soil cloddiness required to withstand wind erosion for certain percentages of time.

D. Conclusions

The solution of the wind erosion problem is dependent on overall progress in basic research, field testing, and extension. It is believed that substantial overall progress has been made towards the solution of the problem. The severity of dust storms in some parts of the Great Plains under similar conditions of drought, temperature, and wind velocity were generally much greater in the 1930's than the 1950's. These differences are believed to be due to better techniques, more favorable financial resources, and more earnest desire on the part of everyone to control erosion by wind.

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CHANGING CONCEPTS OF PLANT NUTRIENT BEHAVIOR AND FERTILIZER USE

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I. Introduction

Agronomists are becoming increasingly aware that only a fraction of the amounts of nutrients necessary to produce top profitable yields is being applied. Fertilizer use first started on the very infertile soils where it

was essential in order to grow any crop. It has gradually spread to areas where the need is not quite so obvious but nearly as great.

Agricultural workers and farmers are continually striving to correct nutrient deficiencies in order that yields will more nearly approach the genetic limits of crop plants. As a result of this effort great progress in the knowledge of plant nutrient behavior and use has been made in the United States and other countries, particularly since the end of World War II.

A significant change is the willingness of the farmer to increase fertilizer usage even in the face of declining farm income. During the five-year period 1951–1955 there was a decline of some 30 per cent in farm income while fertilizer consumption on a plant food basis actually increased 22 per cent. This is a marked departure from the very close relationship between farm income and fertilizer consumption which has always existed in the past.

A. Causes of Increased Use

The quantity of plant nutrients used has increased greatly in the past few years because of quite a number of reasons. A survey of potential fertilizer needs in the United States was conducted by the Fertilizer Work Group of the National Soil and Fertilizer Research Committee (1954). This report fostered a greater consciousness on the part of agricultural workers and the fertilizer industry of opportunities for increased crop production through fertilizer use. Several of the factors which contribute to increased usage of plant nutrients are briefly discussed below.

1. Greater understanding of soil-plant relations and soil chemistry. The research programs in the state and national research agencies are expanding rapidly. Increased emphasis is being given to research on basic soil-fertilizer-plant relationships. Continued effort of this kind leads to improved fertilization practices and a better understanding of the characteristics desired in fertilizers.

2. Improved educational facilities. The more thorough training of agricultural leaders and more intensive extension activities have improved the educational program presented to the farmer. The mass media such as the farm press, television, radio, and demonstrations all aid. The fertilizer industry now employs many commercial agronomists where there formerly were only a few.

3. Soil tests. Soil tests might be considered a connecting link between soils research and the grower. In most cases a lime and fertilizer recommendation based on a soil test will indicate the need for more plant nutrients than the farmer has been using. Fitts and Nelson (1956) reported that in the period 1950 to 1954 the number of soil tests increased 50 per

cent in the United States. Similar increases are taking place in other countries.

4. *Improved fertilizer technology.* Fertilizer manufacture has developed into one of the largest chemical industries. Highly specialized research has led to the production of more efficient and less expensive forms of plant nutrients.

5. *Economics of fertilizer use.* Considerable emphasis is being placed on economic-agronomic studies in order to establish the most profitable levels of fertilization. Last but not least, good prices cause the farmer to have a more favorable attitude and also more money to spend. This brings about a faster adoption of improved fertilizer practices. Periods of lowered prices tax the forward progress of educational programs.

B. Elimination of Plant Nutrients as a Limiting Factor

Yields are limited by the factor which is in least supply. With modern information and technology, plant nutrient supply is one of the easier factors in the environment to control. Norman (1957) brings out an important concept as follows: "It might be pertinent to ask whether there is any way of determining the absolute nutrient requirements of a plant, or whether such information would be meaningful if it were obtained. An ideal nutritional environment indeed may be one in which all nutrient elements are available to the point of slight luxury consumption at all times."

Many agronomists are emphasizing that the farmer cannot afford to have the fertility level any lower than can take advantage of reasonably good rainfall. If adequate rainfall does come, he can capitalize on it. If rainfall is inadequate, the residual plant nutrients for the year following will compensate for lack of initial benefits in most instances. An investment in plant nutrients is the only production cost which is available for use the succeeding year in case of a poor crop year.

Of course under irrigation the grower must bring all the production factors, including nutrient supply, to optimum levels in order to realize full returns from the high cost of irrigation.

C. Fertilizers a Part of a Complete Production Program

To realize the greatest returns from applied plant nutrients other factors in plant growth must be adequately taken care of. Educational programs have recognized this and many "five to ten" step programs have been launched. Points emphasized in addition to plant nutrients include:

1. *Variety of hybrid.* The continuing procession of new varieties or hybrids make for greater responses from plant nutrients. Conversely full expression of genetic potential is not possible without adequate nutrition.

2. *Stands.* High plant population has only recently been stressed and

great improvement has been made in research plots and farmer's fields.

3. *Pest control.* Modern technology has developed new and potent chemicals making weed, insect, and disease control easier and more certain.

4. *Water control.* Drainage, moisture conservation, and supplemental water are of real significance.

5. *Cultural practices.* Cultural practices conducted with precision and on time are possible with the improved and greater capacity farm machinery.

D. Fertilizers Have Effects in Addition to Yields

In addition to the direct effects of plant nutrients on yields there are indirect effects which are coming to the front and which must be considered more carefully in the future.

1. *Quality.* In these days of heavy competition for markets quality of produce is of prime importance. The effect of adequate nutrition on yields and the accompanying effects on crop quality are well known. For example, nitrogen encourages high protein in grain crops such as corn and wheat. Potassium improves the quality of grain crops and certain fruits. Quality of forage from alfalfa-grass mixtures is closely correlated with mineral nutrition. A deficiency of plant nutrients allows grasses and weeds to take over, with the protein and palatability dropping accordingly.

2. *Maturity.* Crops which grow fast are most likely to escape the hazards of the environment. In general the maturity of crops grown on deficient soils is speeded up by addition of adequate nutrients. Dumenil and Shaw (1952) show the effects of nitrogen and phosphorus on corn in Table I.

TABLE I

Effects of Nitrogen and Phosphorus on Maturity of Corn
(Dumenil and Shaw, 1952)

Amount of fertilizer	Date of 75% silking	% Moisture Oct. 10
No fertilizer	Aug. 27	58
80 lb. N	Aug. 24	59
80 lb. P_2O_5	Aug. 17	47
80 lb. N + 80 lb. P_2O_5	Aug. 11	43

3. *Disease.* McNew (1953) states that soil fertility does affect the prevalence and severity of some plant diseases. Some diseases are severe on weakened and undernourished plants. Others are more destructive

when plants are growing vigorously. While there are certain instances where high rates of nitrogen may predispose plants to greater attack by pathogens, in general well-nourished plants are more likely to escape certain diseases. Otto and Everett (1956) report that stalk rot of corn increased with increasing nitrogen application and decreased with increasing potassium application. Younts and Musgrave (1958b) showed that stalk rot incidence was decreased with increasing rate of KCl, but not with K_2SO_4 or KPO_3.

4. *Root development.* The effect of nutrition on development of roots is rather striking (Fig. 1). This is important in longevity of perennials and in standability. The effect of potassium additions in decreasing root lodging and stalk breakage of corn on low-potassium soils is well known.

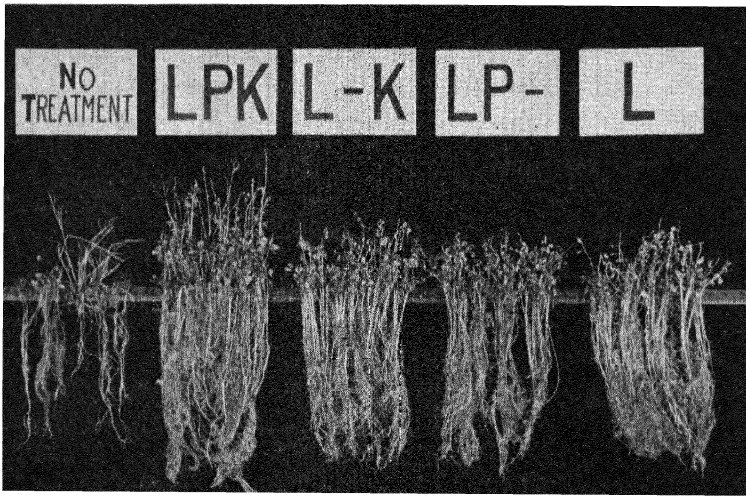


FIG. 1. On this acid infertile soil lime, phosphorus, and potassium were essential for a vigorous root system in summer-seeded alfalfa (Brownstown Soil Experiment Field, Illinois. Photo by H. L. Garrard).

E. CONCEPTS ARE CHANGING

Concepts in regard to plant nutrient behavior and usage are changing rapidly. The purpose of this chapter is to outline some of the developments in respect to diagnostic techniques, sources of nitrogen, phosphorus, and potassium, method and time of application, and residual effects. Relationships to lime, moisture, and grower demands will also be considered.

II. Diagnostic Techniques as a Guide

The selection of the proper fertilizer depends upon a knowledge of the nutrient requirement of the crop and the nutrient supplying power of the soil on which the crop is to be grown. Greater and greater emphasis is being placed on soil and plant diagnostic techniques as a guide to needs. They of course are coupled with past management and sound judgment.

Often diagnostic measurements for examining the ailing plant or soil are thought of as trouble shooting. They are being used in this fashion, but *a more important use is for the prevention of such troubles.*

A. Concepts in Use of Soil Tests

1. *Reporting and Recommendations*

Fitts and Nelson (1956) state that out of 45 states 30 classified soils into four or five categories such as very low, low, medium, high, and very high for P and K. Twelve of the 30 states, as well as the rest of the states, reported pounds per acre.

There is some thinking that three categories are enough—low, medium, and high. This is in recognition of the fact that many factors besides nutrients influence growth of plants in the field. Too, calibrations in many instances may not justify more than three categories. Musgrave (1957) reports that three levels are being used in Ohio. His interpretation is of interest in that at the low level, up to double the plant removal of phosphorus and potassium is suggested in order to allow some build-up in the soil. At the medium level the amount suggested for phosphorus is slightly greater and potassium slightly less than removal. At the high level less than removal is suggested.

The European Productivity Agency of the Organization for European Economic Cooperation (1956) has reported on a comprehensive survey on soil testing in certain European countries. It was concluded that there should be as few levels as possible, the general opinion being three to five.

Bronson and Barber (1957) in Indiana suggest replacement of the phosphorus and potassium removed by crops if the soil test indicates a medium level. With a low soil test this amount is increased by one-third and with a very low test by two-thirds.

2. *Meaning of Soil Tests*

Fitts (1955) has emphasized that soil test levels give an idea as to the probability of response. Soil fertility is only one of many factors in the

environment which influences crop growth, but there will be a greater chance of obtaining a profitable response if the soil tests low than if it tests medium. This concept is presented diagrammatically in Fig. 2. The values are arbitrary but they illustrate the idea of expectation of response. The farmers who are using good management practices will be more likely to risk applying fertilizers, even with a high level of soil fertility.

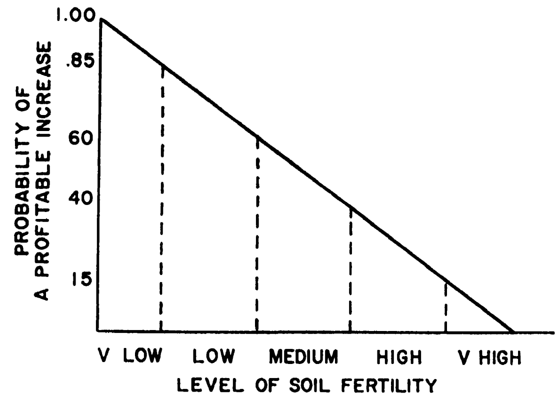


FIG. 2. There is a greater probability of obtaining a profitable response from fertilization on soils testing low in an element than on soils testing medium (Fitts, 1955).

The yield response of corn to phosphorus varies considerably at a given soil test level (Fig. 3). For example on Coastal Plain soils in the 40 to 80 pound range of available P_2O_5 the response to applied phosphorus ranged from about 5 to 30 bushels. With low responses obviously other factors were limiting, such as pests, stand, and moisture.

B. INFORMATION REVEALED BY THE PLANT

Scarseth (1943) has emphasized the need for tests and observations while the crop is growing to help identify limiting factors. Little or no yield response to fertilization tells very little as to actual nutrient needs because of the possibility of other limiting factors. Clement (1948) has relied on crop logging of sugar cane to govern future management practices. One of the important benefits of crop logging or tissue testing has been attributed to the fact that the grower goes out in the field at stated intervals and systematically examines the crop for possible errors in management. Many corn growers may not enter their fields from the time of the last cultivation to harvest.

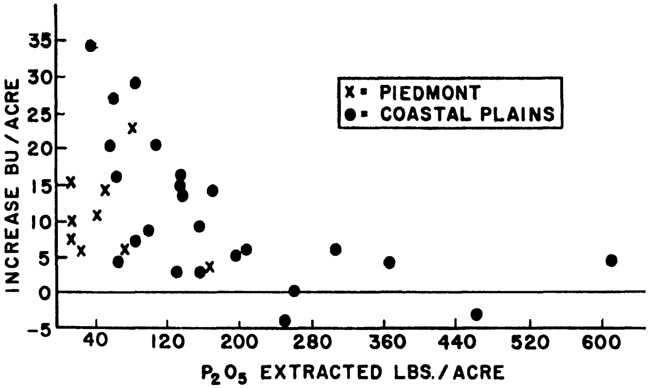


FIG. 3. The response of corn to applied phosphorus varies greatly on low phosphorus soils. Other factors such as stands, pests, and moisture may limit yields (Fitts, 1955).

1. *Deficiency Symptoms*

An abnormal development of the plant may be caused by a deficiency of one or more nutrients. This unusual development is called a deficiency symptom and may be shown in several ways: (a) Severe stunting of the plants. (b) Leaf or stem discoloration or malformation. (c) Quality differences. (d) Delayed or advanced maturity. (e) Obvious yield differences.

Although deficiency symptoms have been valuable in many instances to help identify the cause of trouble there are certain precautions to be kept in mind: (a) It is often difficult to distinguish among several of the symptoms, particularly in the later stages. (b) Disease or insect damage may resemble certain deficiency symptoms. (c) By the time deficiency symptoms of some elements appear a considerable amount of yield has been lost.

2. *Hidden Hunger*

"Hidden hunger" is a term used to characterize a nutrient deficiency which keeps yields below top levels but with no obvious abnormalities in plant growth. A generalized yield response curve as related to the hidden hunger and deficiency symptom zones is shown in Fig. 4. At a low fertility level the plants show deficiencies. However, beyond a certain point few outward symptoms are evident but yields keep increasing with increasing fertility up to a maximum. The point on the response curve beyond which

there are no more deficiency symptoms varies considerably with the various elements.

Chemical tests on the plant are helpful in determining whether the plant has hidden hunger. Soil tests are helpful in avoiding it.

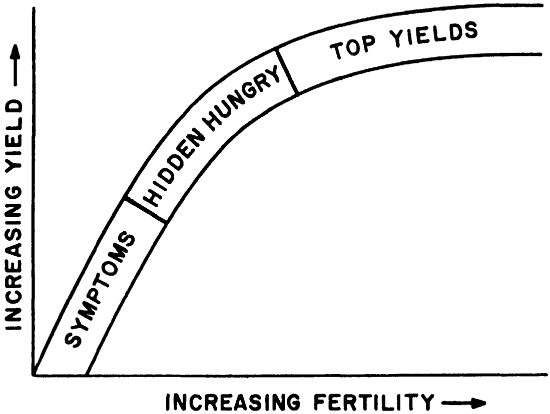


FIG. 4. Yields may be below optimum without the plant showing obvious abnormalities. Hidden hunger may limit yields (Graph courtesy of H. L. Garrard).

3. *Plant Tests*

Rapid tests for the determination of nutrient elements in the plant sap have found an important place in the diagnosis of the needs of growing plants. In these tests the sap from ruptured cells is tested for soluble potassium and unassimilated nitrogen and phosphorus. Hoffer (1926), Krantz *et al.* (1948), Ohlrogge (1956), and Morgan and Wickstrom (1956) are among those who have reported on tissue test activities. These investigators emphasize the need for a knowledge of plant behavior and other environmental factors in order properly to interpret tissue tests.

These tests are of particular aid to a researcher to follow, in a semiquantitative manner, the level of major nutrient elements, and to determine possible limiting factors. Falloon (1956) reports an extensive study in which corn fields in Montgomery County, Missouri were systematically tested to determine the effectiveness of fertilizer recommendations based on soil tests. He found remarkable agreement between tissue tests and fertilizer practices.

In certain states the county agents are equipped for tissue testing. Considering the rapidity of the tests it is unpardonable to guess at the

nutritional status of a plant when a large part of the guesswork can be eliminated.

Total analysis of foliage, particularly of tree crops, is gaining importance as a tool in predicting nutrient status of the plant (Ulrich, 1956; Fisher *et al.* 1957; Walker, 1956). In Michigan a spectrographic analysis service is offered to tree fruit growers.

III. Sources of Nutrients

As pointed out by Newman and Hill (1957) "the development of a new fertilizer to market status is a response to the need for some particular quality or set of qualities that is expected to lower the cost, to provide easier handling, or to supply better soil and crop requirements." One outcome of agronomic research is to help define specifications which will guide the fertilizer chemist or engineer in producing materials having desired physical, chemical, and agronomic characteristics.

A. Nitrogen

1. Soluble Sources

Increasing attention is being directed to relatively new sources such as anhydrous ammonia, urea, and nitrogen solutions for general field use. High analysis and of course cost when applied in the field are of great import. It is of interest that in 1956 anhydrous ammonia constituted 30 per cent of all direct applied N in the United States, more than any other single source.

2. Slowly Soluble Sources

Urea-formaldehyde compounds are sources of slowly available nitrogen in lawn fertilizers. Despite slow initial response of perennial rye grass to such materials, the results over a growth period of 299 days with several clippings showed that the less soluble materials gave a more uniform over-all response than urea and were equally efficient (Armiger *et al.* 1951). Mruk *et al.* (1957) observed that relatively heavy initial application of a urea-formaldehyde compound (8 to 10 lb. N per 1000 sq. ft.) produced good growth response and turf quality with no injury or apparent discoloration on a turf grass mixture. At lower rates (2 to 4 lb.), early response was much slower than from a comparable standard mixture and turf quality was only fair with either material. Scarsbrook (1958) compared urea-formaldehyde preparations with ammonia nitrate on corn and cotton and concluded that the insoluble fraction of the less soluble sources had

no influence on yields. The residual effect was less than from ammonium nitrate on the succeeding oat crop. Crop responses indicated that urea-formaldehyde was about one-half as effective as ammonium nitrate. Advantages of slowly soluble nitrogen sources over soluble sources for fast-growing crops having high nitrogen requirements are yet to be demonstrated.

Results of Winsor and Long (1956) point out a striking negative correlation between soil pH and mineralization of nitrogen from urea-formaldehyde compounds. This contrasts sharply with the relationship in soil organic matter or natural organic materials. In buffered solutions, the urea-formaldehyde materials were 5 to 6 times more soluble at pH 4 than at pH 8. These investigators suggest that for such materials the initial stages of decomposition may be chemical rather than biological.

3. *Factors Influencing Relative Availability of Sources*

Under conditions of rapid nitrification, it is seldom possible to distinguish among the crop responses to commonly used water-soluble sources of nitrogen, including ammonia, urea, ammonium nitrate, nitrogen solutions, sodium nitrate, and ammonium sulfate. Conditions may be defined, however, which give rise to apparent source differences. For example, in very acid soils the nitrification rate is greatly reduced; and as pointed out by Andrews *et al.* (1949), this results in greater retention of anhydrous ammonia than ammonium nitrate when applied in the fall. In contrast, however, ammonium salts top-dressed on alkaline soils may undergo appreciable loss, particularly at high soil temperature, while nitrates are not volatilized. Losses of anhydrous ammonia may result from too shallow placement (Humbert and Ayres, 1957; Stanley and Smith, 1956). Moisture content of soil also may be very important (Fig. 5).

Differences among nitrogen sources often may be attributed to various indirect effects associated with residual soil acidity (Tisdale, 1952). Relatively large applications of ammonium nitrate applied to Coastal Bermuda grass on Cecil sandy loam lowered the pH from 5.7 to 4.9 in only two and one-half years (Abruna-Rodriguez *et al.* 1957). The problem is easily avoided by a judicious liming program.

Acid-forming nitrogen materials, on the other hand, may indirectly enhance phosphorus availability on calcareous soils (Lorenz and Johnson, 1953).

Presence of toxic substances occasionally exerts a direct influence on relative effectiveness of sources. It has been reported for the Great Plains that urea containing an appreciable quantity of biuret when drilled with the seed reduced stands and, hence, yields of winter wheat, oats, and barley. Rai *et al.* (1956) also have noted pronounced detrimental effects

of biuret on beans. On the other hand, Starostka and Clark (1955) have shown that synthetic urea-biuret mixtures (0.5 to 10% biuret by weight) nitrified as readily as did ammonium sulfate. Moreover, where fertilizer was mixed with the soil, experimental urea-biuret mixtures did not adversely affect growth of tomatoes, corn, cotton, and oats, even with 100 lb. of total nitrogen applied per acre.

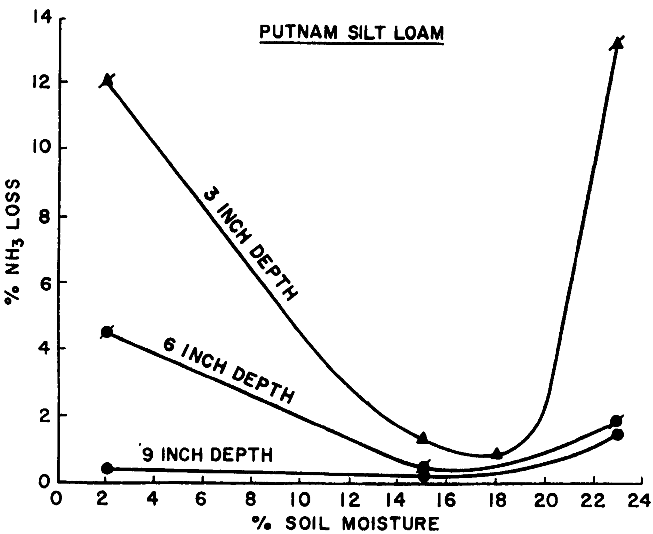


FIG. 5. Losses of ammonia from a Putnam silt loam are influenced by depth of application and soil moisture. Anhydrous ammonia was applied at the rate of 100 lb. of nitrogen per acre in 40-inch spacings (Stanley and Smith, 1956).

B. PHOSPHORUS

Rogers *et al.* (1953) presented a comprehensive review covering much of the pertinent evidence previously reported in this country on comparative efficiency of phosphorus sources. Later, Cooke (1956) summarized results of over 400 field experiments conducted in the period 1940–1953 comparing phosphorus sources in Great Britain.

It is recognized that a number of factors govern the relative behavior of phosphorus sources, aside from the chemical nature of the compounds present. Among the more important of these are kind of crop, soil characteristics, climate, placement of fertilizer, time of application, and rate of application. Characteristics of the fertilizer, other than chemical nature of the fertilizer phosphorus, which frequently modify its effect, are granule size and the presence of non-phosphatic salts.

1. *Water-Soluble Orthophosphates*

a. Importance of water-soluble phosphorus. Investigations during the past several years have resulted in a clearer understanding of water solubility of phosphorus in relation to efficient fertilizer use. For short-season crops which make much of their growth during the cooler months in fall, spring, and early summer (example: small grains for forage), greater efficiency results when a portion of the applied phosphorus is in water-soluble form (Lawton *et al.* 1956; Terman *et al.* 1956). Under climatic conditions of the southern states, however, no consistent advantages of appreciable water-soluble phosphorus in fertilizers for corn, cotton, and small grains grown to maturity have been demonstrated in numerous field trials (Terman *et al.* 1956; Rogers *et al.* 1953).

In the northern part of the United States, phosphorus responses with corn, small grains, and vegetable crops often reflect the proportion of water-soluble phosphorus in the applied fertilizer (Webb, 1955; Pesek and Webb, 1957; Lawton *et al.* 1956) (Table II). Where benefits have been noted, various workers tentatively have concluded that minimum phosphorus water solubility should be around 50 per cent of the total available phosphorus. Lawton *et al.* (1956) reported that granular and pulverant phosphates varying in water solubility were equally effective for corn and wheat when banded. When mixed with the soil the degree of water solubility affected uptake from granular fertilizer but not from pulverant.

TABLE II

Response of Corn to Phosphorus Increased with Greater Water Solubility of Phosphorus (Webb, 1955)

Source of phosphorus	Water-soluble P as % of total P (%)	Yield response[a] (av. of 15 and 30 lb. P_2O_5/A) in 1954 (Bu/A)	Relative response 1954[a] (%)	Relative response 1952, 1953 and 1954[b] (%)
Conc. super	90	11.8	100	100
Nitric phos. No. 1	41	8.9	75	86
Nitric phos. No. 2	14	7.8	66	64
Nitric phos. No. 3	2	3.4	29	—

[a] Average of 4 locations in 1954.

[b] Average of 18 locations in 1952, 1953, and 1954.

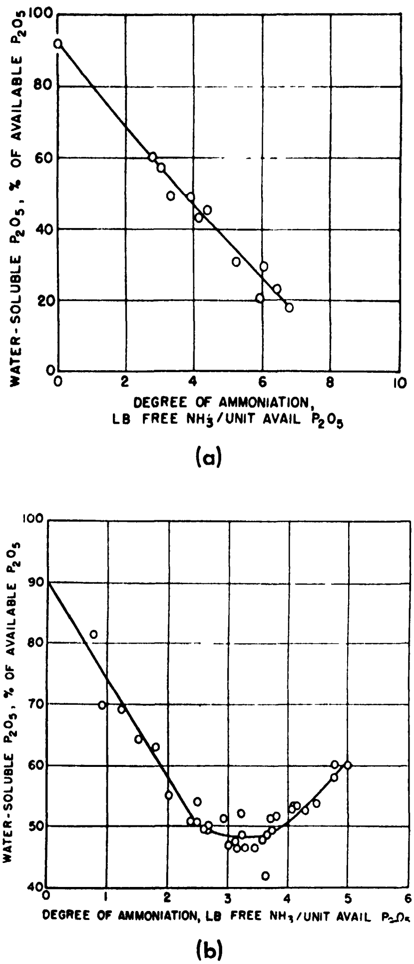
The effects of particle size and placement on availability of water-soluble phosphorus fertilizers apply particularly to acid soils. Increased granular size or localized placement minimize contact between soils and fertilizer. This probably results in higher concentrations of phosphorus accessible to roots in the zones of soil affected by fertilizer. In calcareous soils, on the other hand, little or no effect of granule size on utilization of water-soluble fertilizers has been noted, nor is band placement consistently superior to mixed placement. Research has not supplied an adequate explanation for the interaction of soil pH with granule size and placement. With excess $CaCO_3$ present to react with dissolved fertilizer phosphorus, diffusion distance from the site of application is very restricted (Owens *et al.* 1955; Heslep and Black, 1954) and probably is not affected by particle size to such an extent as has been noted in acid soils.

Ammoniation of superphosphate is an important step in the manufacture of mixed fertilizers. There is a continuous linear decrease in the water-soluble P_2O_5 content of ordinary superphosphate with increasing ammoniation. This is not true with concentrated superphosphate. Regardless of the degree of ammoniation, the water-soluble P_2O_5 does not decrease below about 50 per cent (Fig. 6). Economic factors involved in production of fertilizers of high water-soluble phosphorus content have been discussed by Hignett (1957).

Ammonium phosphates are attracting considerable attention because of complete water solubility. A number of monoammonium phosphate plants are in operation. A few industrial operations are making diammonium phosphate particularly where by-product nitrogen is available.

b. Nitrogen-phosphorus relations. Comparisons of monoammonium phosphate, diammonium phosphate, and superphosphate occasionally indicate a superiority of the ammonium phosphate if relatively low rates, in the range of 20 to 40 lb. P_2O_5 per acre, are applied (Mitchell, 1957; Olson and Dreier, 1956b). Olson and Dreier (1956b) observed an early effect of associated nitrogen fertilizer on uptake of phosphorus by wheat and oats under a wide range of soil conditions. The effect was pronounced in the range of 10 to 20 lb. applied nitrogen per acre. Intimate association of nitrogen and phosphorus was a key factor. With low rates of phosphorus (10 to 20 lb. P_2O_5), the effect of associated nitrogen was equivalent to doubling the rate of phosphorus application. The beneficial influence upon phosphorus uptake of placing nitrogen and phosphorus fertilizers in close association also has been reported by Fine (1955), Robertson *et al.* (1954b), and Ohlrogge *et al.* (1957) (Fig. 7).

There was evidence (Olson and Dreier, 1956b) that nitrogen-phosphorus combination resulted in greater root proliferation in the fertilizer



a. (*Top*) Ordinary superphosphate b. (Bottom) Concentrated superphosphate

FIG. 6. Influence of degree of ammoniation on the solubility of phosphorus in ordinary and concentrated superphosphate (Hignett, 1957).

zone than with phosphorus alone. A physiological influence of nitrogen on root activity also has been postulated. Ohlrogge *et al.* (1957) emphasize the complexity of the root environment in the fertilizer band where a number of fertilizer and soil chemical reactions and plant physiological responses are taking place.

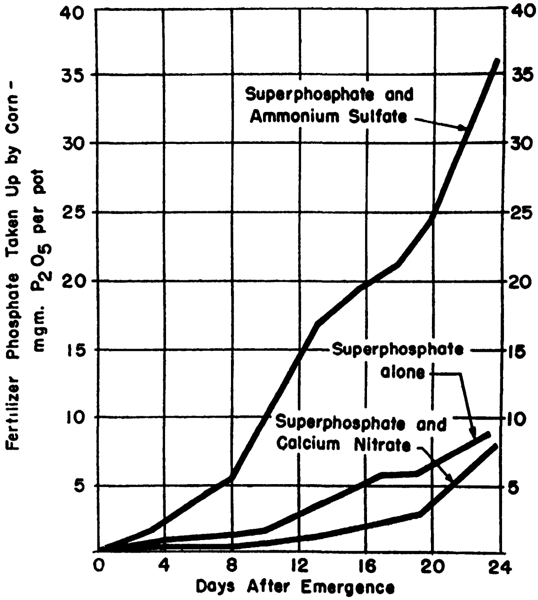


FIG. 7. Nitrogen mixed in the fertilizer band with phosphorus increases the uptake of phosphorus. Ammonium sulfate is more effective than calcium nitrate (Ohlrogge *et al.*, 1957).

Questions have been raised concerning the balance among anions in plants. The important anions involved in fertilizers are $H_2PO_4^-$, NO_3^-, SO_4^- and Cl^-. Much of the attention is focused on the effect of the latter three on phosphorus uptake.

Ammoniacal nitrogen is more effective than nitrate nitrogen in increasing phosphorus absorption (Olson and Dreier, 1956b; Ohlrogge *et al.* 1957). In fact the latter investigators showed that $Ca(NO_3)_2$ depressed absorption (Fig. 7). Mention of the effects of Cl^- and SO_4^- will be made in Section III, C, 1.

Heslep and Black (1954) found that the distance of phosphorus diffusion in soil was greater from a band of monoammonium phosphate than from superphosphate. This may be accounted for by precipitation of a portion of the phosphorus in the form of dicalcium phosphate at the band site (Brown and Lehr, 1956; Lehr *et al.* 1959). This occurrence conceivably offers a partial explanation for the superiority of ammonium phosphates over superphosphate observed by Mitchell (1957) and Olson and Dreier (1956b), since with ammonium phosphate a water-insoluble residue does not form at the site of application. Moreover, a strongly acidic solution

(pH 1 to 1.5) emerges from the superphosphate (Lindsay and Stephenson, 1957), whereas the solution of monoammonium or diammonium phosphate is expected to range from moderately acid to near neutral.

Bouldin and Sample (1958) placed pellets of monocalcium phosphate-salt mixtures in soils and studied the distribution of water-soluble and total fertilizer phosphorus around the pellets. The quantity of soluble phosphorus per unit weight of soil in the fertilizer zone affected by fertilizer was greater when the pellet contained NH_4NO_3 or other salts than in the absence of salts. This is explained in part by the fact that a smaller residue of dicalcium phosphate was left at the pellet site where salts were present. The nature of soil-phosphorus reaction products formed in the vicinity of the pellet might also have been modified by the various salts. Laboratory observations correlated well with plant availability in these studies.

c. Liquid fertilizers. Phosphoric acid, H_3PO_4, applied in irrigation water was about as available as monoammonium phosphate or concentrated superphosphate applied in the band on a soil of pH 8 (Schmehl *et al.* 1955). On another calcareous soil, Fuller (1953) found indications that liquid H_3PO_4 was more effective for cotton than superphosphate or ammonium phosphate. Considerable increase has occurred in recent years in the use of liquid ammoniated phosphoric acid (Slack, 1955; 1957). Limited evaluations indicate that phosphate compounds in solution are as effective as water-soluble solid materials in supplying phosphorus to the crop when comparable placements are used. A number of studies comparing liquid and solid materials are in progress but few results have been reported.

2. *Relatively Water-Insoluble Orthophosphates*

a. Dicalcium phosphate. The principal water-insoluble phosphorus compound produced upon ammoniation of superphosphates and in production of nitric phosphates is dicalcium phosphate. Variable quantities of hydroxyapatite or fluorapatite may form depending on conditions and degree of ammoniation (Lehr, 1955). Usually, anhydrous dicalcium phosphate, $CaHPO_4$, forms at the relatively high temperatures reached during ammoniation and granulation. At low temperatures of ammoniation, $CaHPO_4 \cdot 2H_2O$ may be present in appreciable amounts.

Recently, $CaHPO_4 \cdot 2H_2O$ became of particular interest, since this metastable compound was observed frequently as the residue which remained at the pellet site upon dissolution of concentrated superphosphate granules in soils (Brown and Lehr, 1959). Subsequently, the relative crop responses to anhydrous and hydrated forms of dicalcium phosphate and concentrated superphosphate have been studied in the greenhouse using

acid, limed acid, and calcareous soils. Consistently, the $CaHPO_4 \cdot 2H_2O$ was more available to plants than $CaHPO_4$, and under certain conditions was equal to superphosphate (Terman *et al.* 1958) (Table III). Additional evidence in support of these findings recently has been obtained by Bouldin (unpublished data). Cooke (1956) compared a pulverant dicalcium phosphate containing 39 to 40 per cent P_2O_5 (probably the dihydrate) with ordinary superphosphate, and concluded that the dicalcium phosphate dihydrate could replace superphosphate for many crops on slightly acid or acid soils, but might not be quite as satisfactory on calcareous soils or for crops requiring a rapid start. Similar conclusions were drawn by Rogers *et al.* (1953).

TABLE III

Yield of Rye Grass on Five Soils Fertilized with Various Calcium Phosphates Supplying 40 lb. P_2O_5 (Terman *et al.* 1958)

P compound and placement	Yield of dry matter (grams per pot)[a]				
	Hartsells sandy loam pH 5.1	Clarksville silt loam pH 6.0	Edina silt loam pH 5.5	Rosebud loam pH 8.0	Webster clay loam pH 8.3
No phosphorus	0.15	0.35	4.13	5.95	5.24
In layer					
$CaHPO_4$	6.79	8.16	8.76	6.74	6.55
$CaHPO_4 \cdot 2H_2O$	7.66	8.43	9.27	7.00	7.60
$Ca(H_2PO_4)_2 \cdot H_2O$	6.31	7.60	9.59	7.51	8.44
Mixed with soil					
$CaHPO_4$	0.49	2.94	7.04	6.36	7.56
$CaHPO_4 \cdot 2H_2O$	1.43	3.85	8.75	6.39	8.32
$Ca(H_2PO_4)_2 \cdot H_2O$	0.88	2.64	7.37	6.32	7.98

[a] LSD for comparison among phosphates for each soil and placement = 0.89 (5%) and 1.18 (1%).

In most of the tests conducted in this country with straight dicalcium phosphate, analyses indicate that the anhydrous form was used. In experiments with ammoniated superphosphates, generally, it is not known whether the dicalcium phosphate was in the anhydrous or dihydrate form. This points to the need for better characterization of experimental materials.

b. Leached zone phosphate. A process for utilizing low-grade leached zone Florida ores, containing 10 to 15 per cent P_2O_5, in fertilizer production has been developed by the Tennessee Valley Authority (Hignett *et al.* 1957). Phosphorus minerals in the ore include wavellite, millisite, pseudo-

wavellite, and small amounts of apatite, together with some clay and an abundance of silica sand. The fertilizers produced from the nitric acid extract of leached zone ore contain some ammonium phosphate and calcium phosphate and appreciable amounts of amorphous aluminum phosphates. Generally, field and pot tests indicated that the high-alumina phosphate fertilizers having 20 to 30 per cent of the phosphorus in water-soluble forms were 90 to 95 per cent as effective as superphosphate for cotton, small grains, and corn (DeMent and Seatz, 1956).

Materials containing less than 10 per cent of the phosphorus water soluble were less effective than nitric phosphates or superphosphate when used as a starter row application for corn (DeMent and Seatz, 1956) or for rye grass (Starostka *et al.*, 1955).

c. Phosphorus compounds in granular mixed fertilizers. During the manufacture of complex mixtures, such as are produced in modern ammoniation-granulation plants, the reactions which take place can result in a variety of phosphorus compounds. Moreover, various nonphosphatic salts which form or are introduced become intimately mixed with the phosphorus compounds.

Starostka and Hill (1955) observed that both solubility of dicalcium phosphate and its availability to plants were increased by intimate association with salts such as ammonium sulfate, monoammonium phosphate, and others which commonly occur in homogeneous mixed fertilizers. In this connection, the practice of using granular KCl and granular superphosphate as cores of larger granules in production of mixed fertilizers is of interest (Hignett and Slack, 1957). This results in less intimate association of the components.

Moreover, the state of subdivision of particles within the granule, density or hardness, interactions of the components, and other factors which govern phosphorus concentration in the dissolved phase and the penetrability of the granule conceivably influence phosphorus availability to plants. These factors are under consideration in researches now underway in various soil and fertilizer laboratories.

3. *Compounds Other Than Orthophosphates*

a. Calcium metaphosphate (0–62–0). Rogers *et al.* (1953) concluded that calcium metaphosphate (CMP) was fully as effective as concentrated superphosphate (CSP) in a large number of experiments with cotton, corn, wheat, and legume hay conducted on acid soils of the Southeastern states. Except where some water-soluble phosphorus is needed for a rapid starter effect (see Section III, B, 1, a), CMP also has compared favorably with CSP on acid to neutral soils of the Midwest. In this area, it appears that best efficiency is obtained by broadcasting and disking or plowing

down of CMP. Mixing with the soil hastens solution and hydrolysis to orthophosphate. In a more recent summary, Terman and Seatz (1956) drew similar conclusions and also reported that CMP was slightly inferior to CSP on acid to neutral soils as a source for potato and vegetable crops. There was no source × liming interaction on acid soils.

Schmehl *et al.* (1955) on calcareous soils found that first-year effects of CMP (minus 40 mesh) were generally equal to CSP, except when top-dressed on alfalfa under poor moisture conditions, side-banded at planting, and, in one instance, when plowed under shortly before planting. Residual effects measured after the first year consistently have equalled that of CSP.

Pesek (1955) reported no difference in yield response to CMP (minus 40 mesh) and CSP top-dressed on legume-grass meadows. While uptake of fertilizer phosphorus was considerably less from minus 40-mesh CMP at the first cutting, little difference was evident at the second cutting on an acid and slightly alkaline soil. However, CSP continued to supply more phosphorus on a calcareous soil. This effect of time on increasing availability of CMP has been noted by others (Schmehl *et al.* 1955).

Calcium metaphosphate alone cannot be ammoniated, and until recently this has reduced its usefulness in mixed fertilizers. A process has been developed, however, whereby it can be hydrolyzed with sulfuric acid. This makes possible its use in mixed goods when ammoniation is desired. This development is of interest in that calcium metaphosphate, a high-analysis solid source of phosphorus, can be manufactured at the mines, shipped to the fertilizer plant, and then utilized.

b. Other non-orthophosphates. Ammonium metaphosphate (17–73–0), produced by reaction of NH_3 and P_2O_5 has been compared with CSP and other phosphorus sources in greenhouse tests (Stinson *et al.* 1956), and in a number of field experiments the results of which are unpublished. In general, the material appears to be as available as superphosphate.

The liquid phosphoric acid produced by further introduction of P_2O_5 into orthophosphoric acid contains about 50 per cent of its phosphorus principally in the form of pyrophosphoric acid (Striplin *et al.*, 1957a). Liquid fertilizers prepared by ammoniation of the "superphosphoric acid" appear to be at least equal to dissolved diammonium phosphate and CSP as sources of phosphorus, indicating a ready availability of the pyrophosphate fraction (Striplin *et al.* 1957b).

4. *Initial and Residual Effects of Phosphorus Sources*

Reference already has been made to experiments in which crop responses obtained were related to degree of water solubility of the phosphorus. It should be pointed out, however, that in many of the experiments where no effects of phosphorus source on final yield were evident, early

growth effects often were marked. More specific information is needed to better establish the relations between time of uptake of phosphorus by the crop and yield effects. Using water-soluble or liquid materials, opportunities may exist to effectively supplement initial phosphorus during the season. There has been little exploration of this possibility.

Residual effects of phosphorus sources, ranging widely in initial characteristics or in relative effects on the crop to which applied, seldom differ significantly after the first year. This has been demonstrated by Schmehl *et al.* (1955) working with calcareous soils and by Ensminger and Pearson (1957) using acid soils. In the latter study, differences in residual effect of basic slag, ammonium phosphate, and other phosphorus sources, clearly were related to pH effects. Cooke (1956) found no clear indications of differences in the residual values of the phosphate sources tested. It was concluded, in agreement with findings in this country, that "it is generally unjustifiable to claim that prolonged action compensates for the low immediate value of some of the less-soluble forms of fertilizer." Of far greater practical importance are the problems and practices involved in obtaining improved efficiency on the crop fertilized.

C. Potassium

1. *Soluble Sources*

Muriate of potash (KCl) and sulfate of potash (K_2SO_4) have for many years been the chief sources of potassium throughout the world. Both salts readily dissolve in soil water, and a large proportion of the potassium ions are rendered relatively immobile, though accessible to plant roots, because of the capacity of most soils to hold considerable quantities of cations in exchangeable and nonexchangeable form.

Over 90 per cent of the fertilizer potassium consumed in the United States is potassium chloride. Sulfate of potash and sulfate of potash-magnesia make up almost all of the remainder. There is some interest in nitrate, carbonate, and phosphate forms. The salt indices of various sources are given in Table IV.

TABLE IV

The Salt Index of Various Sources of Potassium

	Salt index per unit of K_2O
Manure salts	5.636
Sulfate of potash-magnesia	1.971
Potassium chloride	1.936
Potassium nitrate	1.580
Potassium sulfate	0.853

The higher the value, the more likely it is that the source will injure plants if placed close to the roots, although, as indicated earlier, reaction with soil occurs readily. The importance of precision and proper placement, however, should be recognized.

Except for certain specialized crops, one potash carrier is as effective as any other. For example the quality of tobacco, and in some instances potatoes, is affected adversely by excessive amounts of chloride. Of course, these crops may require from 100 to 300 lb. or more of K_2O per acre annually. In such instances sulfate of potash may furnish a portion or all of the potash. It is of interest, however, that in Holland muriate of potash is broadcast in the fall preceding the spring planting of potatoes. Presumably, this method allows for the leaching out of chloride by fall and winter rains (Nelson, 1957).

Studies by Ohlrogge (1957) show that salts with a common cation such as potassium, but with varying anions, vary in effect on phosphorus uptake by *young corn plants* as measured by P^{32} (Fig. 8). In general, anion effects on phosphorus uptake tend to decrease in the following order: $H_2PO_4 > SO_4 > Cl = NO_3 > HCO_3$. With chloride as the common anion, phosphorus uptake tends to decrease as follows: $Na > K > H > Li$.

Measurements of total phosphorus at bloom or near maturity showed little effect due to chloride (Fine, 1955; W. H. Pierre cited by Nelson, 1957; Younts and Musgrave, 1958b). Younts and Musgrave (1958a) compared KCl and K_2SO_4 in the row for corn in two experiments. At the 20-pound rate the plants receiving KCl tended to make more rapid early growth and be somewhat more advanced in maturity than those receiving K_2SO_4. In one experiment the KCl gave a significantly higher yield. At the 120-pound rate K_2SO_4 was superior in terms of growth and maturity and gave a higher yield than KCl in one experiment.

Corn tends to restrict Cl in the leaves to less than 1.0 per cent. On the other hand chloride in tobacco may exceed 6 per cent. It is of interest that corn is being grown under conditions of high chloride in the soil on the irrigated soil of the West.

It is clear that there is anion competition early in the life of the plant. As yet the effects are of such a magnitude that no consistent influence on yield has been shown. Further research is needed on interrelationships among the anions and relation of these early effects to growth and quality of product.

2. *Slowly Soluble Sources*

Very sandy soils have a low retentive capacity for applied soluble potassium. For such soils, a slowly soluble source of potassium, which releases potassium at a sufficiently rapid rate for the crop and is less subject

to leaching would be of value. Lunt and Kwate (1956) conducted greenhouse experiments using glass frit containing about 36 per cent K_2O, and prepared by fusing orthoclase feldspar and KNO_3 or K_2SO_3 at high temperature. The product dissolved slowly in water, yet furnished adequate

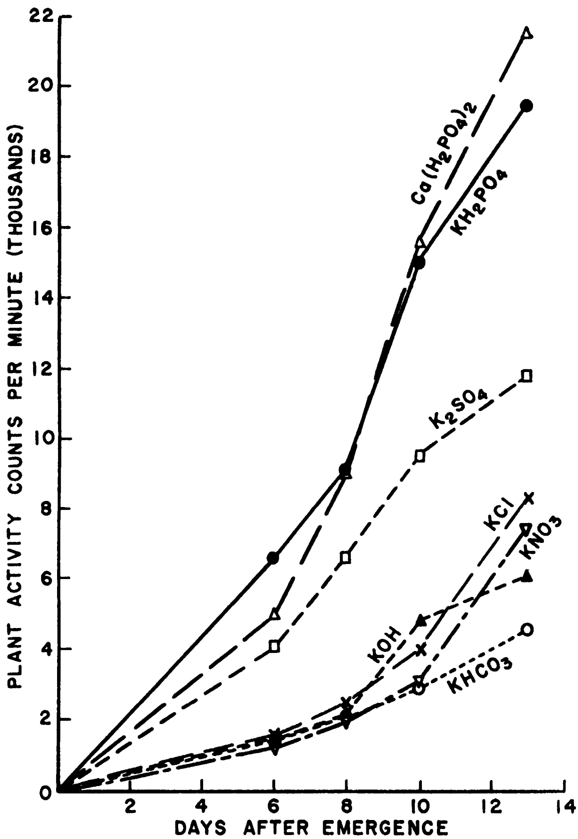


FIG. 8. The anion has a marked effect on uptake of phosphorus by *young corn.* Uptake of phosphorus is expressed as plant activity since P^{32} was used (Ohlrogge, 1957).

quantities of potassium for carnations, cotton, and various commercial greenhouse plants. Upon moist storage of soil-frit mixtures, potassium was gradually released. Coarser particles (28–48 mesh) were weathered more slowly than −200-mesh particles. The principal advantage, deduced from comparing KCl, K_2SO_4, and frit for bench-grown carnations, was that the

less soluble material could be applied in a single large application without danger from salt effects.

On a pilot plant scale, the Chemical Development Branch, Tennessee Valley Authority, has prepared potassium metaphosphate (0–47–28) and a material consisting largely of potassium-calcium pyrophosphate (0–35–25), which currently are being compared with KCl in field tests on cotton, corn, and legumes. The −35-mesh materials contain about 30 per cent of the potassium in water-soluble form, attributable in part to the presence of unreacted KCl. Preliminary field studies with these potassium phosphates are designed to reveal any advantages from using less soluble materials containing low content of chloride, and the effect of particle size (−35 vs. −6 + 14 mesh).

Greenhouse studies with laboratory preparations of potassium-calcium pyrophosphate ($K_2CaP_2O_7$) have revealed that uptake of potassium by plants is directly related to initial solubility during initial short periods of soil-fertilizer contact. However, alfalfa and corn grown for a few months derived as much potassium from the ground pyrophosphate (−35 mesh) as from KCl. The latter was more rapidly leached from a sandy soil (DeMent and Stanford, 1958). As suggested by data of Lunt and Kwate (1956), particle size control appears to offer a means of governing rate of dissolution and, hence, potassium uptake by plants.

IV. Fertilizer Placement

Proper placement is important for two main reasons: (a) Prevention of injury to the plant. (b) Efficient utilization by the plant.

The problem of improper fertilizer placement is not a new one. However, it is becoming of decidedly greater concern because of the increase in concentration and rates of fertilizers. For example Table V shows this for the Northeast (York, 1957).

TABLE V

Changes in Fertilizer Concentrations and Rates in the Northeast

	Average analysis of mixed fertilizers in N.E. United States			Plant food usage in Northeast		
Year	N (%)	P_2O_5 (%)	K_2O (%)	N (lb./A)	P_2O_5 (lb./A)	K_2O (lb./A)
1935	3.7	9.7	7.2	4.8	13.3	7.2
1955	5.5	11.5	10.6	17.6	34.2	29.7

In the Midwest in 1949 2–12–6 was the most popular fertilizer grade. In 1958 such grades as 4–16–16 and 5–20–20 are among the most popular for corn. The 2–12–6 has a total of 8 units of N plus K_2O while the 4–16–16 and 5–20–20 have 20 and 25 respectively. Similar changes have taken place in the South and the West.

These trends demand an increased emphasis on precision placement in order to avoid a concentration of soluble salts in contact with the germinating seed. Many agronomists feel that improper placement has been limiting fertilizer responses.

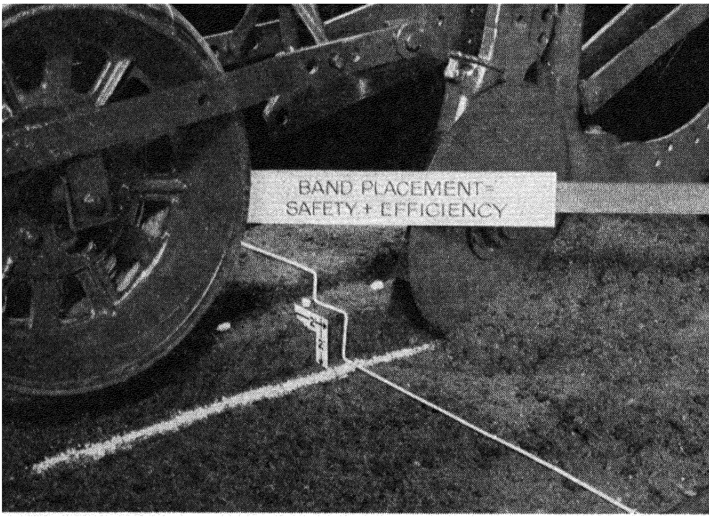


FIG. 9. Placement of row fertilizer to the side of and below the seed helps to avoid damage from soluble salts and makes for greater efficiency. The nutrients are placed in the root zone rather than near the surface (Photo by H. L. Garrard).

A. BAND PLACEMENT FOR ROW CROPS

1. Corn

The importance of placing the planting fertilizer in a band to the side of and below the seed has been recognized for many years (Fig. 9). In 1948 the National Joint Committee on Fertilizer Application stated that high rates of fertilizer for corn at planting should be drilled in a continuous band approximately 2 inches to one side and about 2 inches below the level of the seed. The Committee released similiar information in 1958.

Early work on this problem was conducted in many states. More recently a series of papers by Cook (1957), Ohlrogge *et al.* (1957), Satchell (1957), and Tisdale (1957) has helped to give renewed emphasis to the problem. In general agronomists feel that if growers were in a position to apply larger quantities of fertilizer safely, higher rates would be recommended.

The split boot applicator has been used for many years for corn and soybeans. It often places the fertilizer above the seed level and very close to or with the seed. In dry springs such a placement has been harmful to stands of row crops. Too, phosphorus does not move and it may be in a less effective position as far as plant roots are concerned. Compactness of seed bed, degree to which the boot is worn, and speed of planting all affect the point of placement with a split boot.

Examples of response of corn to side-band placement have been published by MacGregor and Johnson (1956) and Millar *et al.* (1947). (Table VI).

TABLE VI

The Response of Corn to Side-Band Placement

	Increase in yield from 200 lb. 5–20–20[a] (Bu/A)	Increase in yield from 400 lb. 3–12–12[b] (Bu/A)
Standard split boot	6.8	3.3
2 inches below and 2.5 inches one side	10.7	9.5

[a] MacGregor and Johnson (1956).
[b] Millar *et al.* (1947).

2. *Vegetable Crops*

The same type of placement recommended for corn is generally recommended for many vegetable crops. However, as more work is carried out on certain crops the feasibility of more precise placements may be determined. This might be true particularly for those fast growing crops with quite limited root systems. For example, Davis *et al.* (1956) point out a trend toward higher yields of onions when fertilizer was placed either 2 or 3 inches below the seed rather than 1 inch to the side of and 2 inches below.

Cooke (1954) emphasized that in developing placement methods for new crops, root systems must be studied. He points out the nitrogen, phosphorus, and potassium, placed near the seed of peas, each stimulated extra root growth.

B. Band Placement for Small Grains

In 1948 the National Joint Committee on Fertilizer Application advocated placement of fertilizers in partial contact with the seed of small grains. The Committee emphasized that some stand loss is not as serious as with most other crops because of heavy seeding rates and subsequent stooling.

TABLE VII

The Effects of Moderate Rates of Nitrogen on Germination of Small Grain (Olson and Drier, 1956a)

Crop	Maximum germination % of control
Wheat (NEBRED)	45
Barley (SPARTAN)	48
Rye (PIERRE)	67
Oats (NEMAHA)	70
L.S.D. (05)	6

The change to heavier rates of higher analysis fertilizers appears to be causing delayed emergence of small grains under low soil moisture, however. Olson and Dreier (1956a) have noted severe stand reduction and yield losses as a result of moderate rates of nitrogen. These investigators found that effects on germination were more marked on wheat than on oats (Table VII).

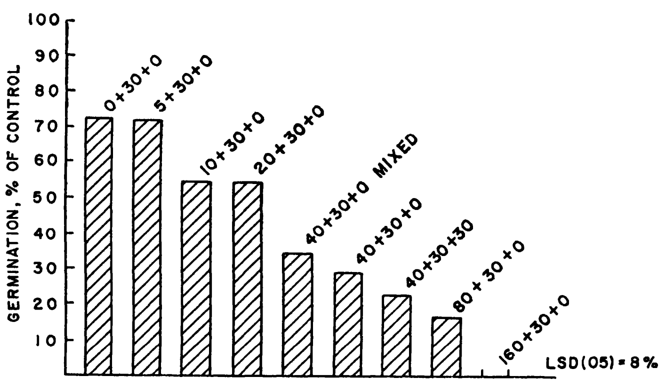


FIG. 10. Effect of rate of nitrogen on germination of wheat under critical soil moisture (soil at ¼ available water capacity for 10 days followed by simulated rain; fertilizer at seed level except as indicated) (Olson and Dreier, 1956a).

Olson and Dreier (1956a) found that inclusion of high rates of nitrogen with phosphorus reduced stands of wheat markedly under rather critical moisture conditions (Fig. 10). Calcium cyanamid, ammonium hydroxide, and urea were the most detrimental of a number of nitrogen sources. Phosphorus carriers likewise behave differently and ammonium phosphates caused the greatest losses in germination (Fig. 11). Potassium with the seed likewise reduced germination and yield.

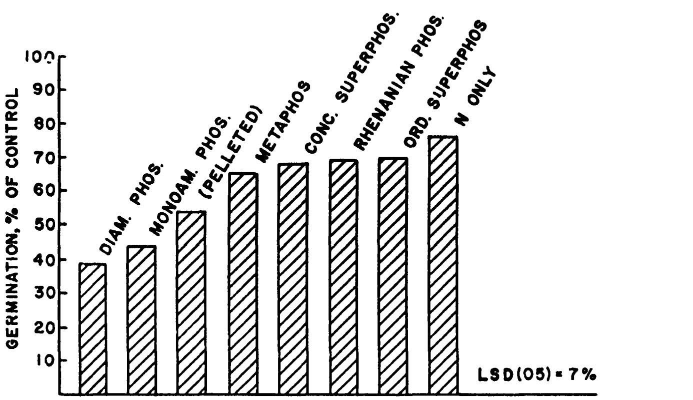


FIG. 11. Effect of phosphorus carrier on germination of wheat under critical soil moisture (soil at ⅓ available water capacity for 8 days followed by simulated rain; 40 + 50 + 0/A applied with seed) (Olson and Dreier, 1956a).

Guttay (1957) observed that a complete fertilizer or a nitrogen-phosphorus mixture in contact with the seed had marked detrimental effects on emergence of wheat. Somewhat less harmful were the nitrogen-potassium and phosphorus-potassium mixtures. Placing the fertilizer 1 inch to the side and 1 inch below eliminated the problem (Fig. 12). Cook (1957) reports that 300 lb. of 5–20–20 in contact with wheat seed injured stand. No ill effects were obtained with 900 lb of 5–20–20 placed to the side and below the seed.

Olson and Dreier (1957) suggest a complete separation of wheat seed and fertilizer by banding the fertilizer 1 to 2 inches to the side and slightly below the seed row. Prumel (1956) states that fertilizers for oats should be placed in a band 2 centimeters to the side and 4 centimeters below the seed.

C. Band Seeding for Legume-Grass Mixtures

An important problem over the years has been to get a good stand of vigorous legume grass seedlings. Several investigators have experi-

mented with placement of fertilizer directly under the drill row of forage plants at seeding. Wagner and Hulbert (1954) show that fertilizer banded 1 inch below is superior to broadcast or placement 1 inch to the side and 1 inch below (Fig. 13). Cooke (1954) also reports that lucerne seedlings,

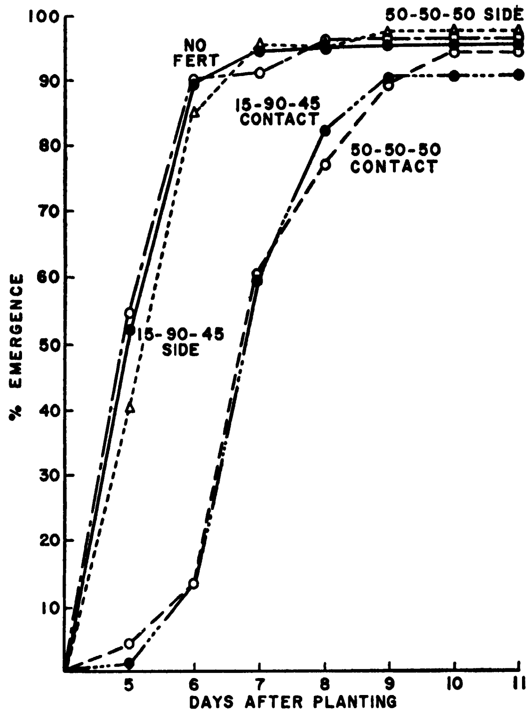


FIG. 12. Placement of the fertilizer one inch to the side and one inch below the wheat seed as compared to contact placement speeds up emergence (Guttay, 1957).

because of long straight tap-roots and very few lateral roots are unable effectively to use phosphorus to the side. Phosphorus placed below is in the path of the developing plant root.

There is evidence that packing the seed row after band seeding is of importance. Tesar (1957) states that packing after drilling resulted in stands 28 to 109 per cent better than stands established without packing in three years of tests. Data from Illinois by Carmer (1957) are of interest (Table VIII).

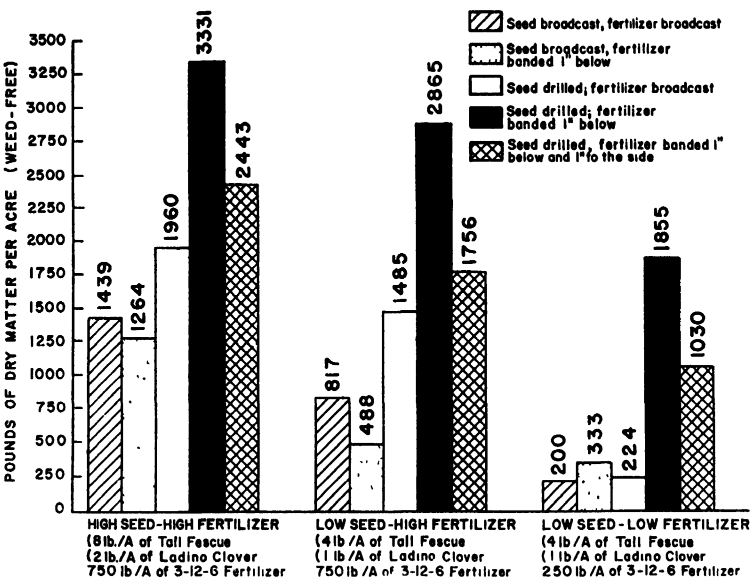


FIG. 13. Placing fertilizer directly below Ladino clover and fescue seed is superior to broadcast or placement one inch to the side of seed (Wagner and Hulburt, 1954).

D. BROADCAST APPLICATIONS

Soil tests are showing many soils to be quite low in phosphorus and potassium. Under these conditions most official agencies recommend corrective amounts of phosphorus and potassium broadcast and a portion at planting.

TABLE VIII

First-Cutting 1956 Alfalfa Hay Yields from 1955 Late-Summer Seedings (Carmer, 1957)

Treatment	T/A
Seed and fertilizer broadcast	0.84
Seed broadcast, no fertilizer	0.23
Seed and fertilizer band placed	1.31
Seed band placed, no fertilizer	0.47
Seed and fertilizer broadcast, rolled	1.13
Seed and fertilizer band placed, rolled	1.54
Seed broadcast, no fertilizer, rolled	0.58
Seed band placed, no fertilizer, rolled	0.43

1. *Phosphorus*

A number of states suggest heavy broadcast applications and small row applications on the more responsive crops grown on low phosphorus soils. For example Bronson and Barber (1957) suggest that the phosphate soil test be built up to 180 pounds for maximum yields, the border line between medium and high according to the Purdue system. They indicate that row applications of phosphorus are generally needed for corn and small grains, however.

More recent results by Barber (1958) for a corn-soybean-wheat-hay rotation on a dark, central Indiana soil suggest that if the soil is built up high enough in phosphorus, row applications are not needed for corn and wheat (Tables IX and X). In fact it was possible to obtain highest yields of corn only by building up the soil phosphorus level. He points out, however, that the medium level with a small row application was most profitable.

TABLE IX

Effect of Row Application and Soil Phosphorus Level on Corn Yield (six-year average) (Barber 1958)[a]

Row application (P_2O_5 lb./A)	Soil level—available P_2O_5 (lb./A)		
	80	140	250
	bu/A	bu/A	bu/A
0	—	116	117
10	106	114	117
25	109	115	115
50	107	—	—

[a] Adequate N and K applied.

TABLE X

Effect of Row Application and Soil Phosphorus Level on Wheat Yield 1956 (Barber 1958)[a]

Row application (P_2O_5 lb./A)	Soil level—available P_2O_5 (lb./A)		
	80	140	250
	bu/A	bu/A	bu/A
0	33	45	58
30	54	55	60
75	59	61	56
150	61	—	—

[a] Adequate N and K applied.

On soils low in phosphorus and with the application of modest amounts broadcast applications are inefficient for most crops. For example, Davis *et al.* (1956) report that 50 + 100 + 200 per acre broadcast produced a little more than half the yield of onions obtained when placement was 2 inches below the seed. This is largely a phosphorus effect. Too, Cooke (1954) states that generally speaking small grain as well as several other crops would require twice as much complete fertilizer if it were broadcast rather than drilled in the row.

2. *Potassium*

Building up to high levels of potassium is not generally recommended because of possible luxury consumption by hay crops and possible fixation by the soil. However on low potassium soils heavy broadcast applications are often recommended once or twice in the rotation. If sufficient potash is broadcast periodically Bronson and Barber (1957) state that row applications are not necessary unless the soil test is low. On soils medium or above in potassium level, maintenance needs can be met with either broadcast or row applications.

Work by Barber (1959) showed the importance of building up the potassium soil levels for corn (Table XI). The highest level was most profitable. It would be of interest to know the effect of a higher amount of K_2O in the row at the lowest soil level.

TABLE XI

Effect of Row Application and Soil Potassium Level on Corn Yields (six-year average) (Barber, 1959)

Row ($lb. K_2O/A$)	Soil level of available potassium, (lb./A.)		
	100	150	300
	bu/A	bu/A	bu/A
0	97	110	117
25	110	112	—

Russell (1956) reports that Danish and Dutch scientists have found large amounts of potash to be necessary to correct potassium deficiency on potatoes grown on low potassium soils. An application of 240 pounds K_2O was not sufficient but 480 pounds K_2O was. These scientists feel that a heavy application once every 5 years is better than a light application every year. Apparently it is important that the applied potassium distribute itself evenly over the soil particles. Likewise massive applications have been found necessary on certain tree crops grown on low potassium soils in this country.

E. Foliar Applications

The addition of nitrogen, phosphorus, and potassium directly to the leaves of plants presents problems in applying adequate amounts without causing severe burning of leaves and without using an unduly large volume of solution. Foliar sprays employing urea to supply nitrogen have been successfully used on such crops as apples and citrus. Such foliar sprays on small grain, cotton, and corn are no more effective than soil applications, however. Finney *et al.* (1957) sprayed urea on wheat during the fruiting period and increased the protein from 9.3 to 16.1 per cent.

Volk and McAuliffe (1954) found greater absorption of nitrogen from urea at night than in the daytime by tobacco. Absorption was increased by injuring the epidermal hairs or decreased by adding sucrose. Both Foy *et al.* (1953) and Volk and McAuliffe (1954) found that sucrose reduced leaf burn from urea. Potassium-containing sprays have been used for a few crops, among them apples, celery, and pineapples.

Teubner *et al.* (1957) found that bean leaves were more retentive of nutrient sprays and that absorption was more rapid than with tomato leaves. They feel that foliar sprays of phosphorus may serve as a supplemental source of this nutrient during critical stages of plant development when root absorption is limited by soil fixation, low soil temperatures, and other adverse conditions. Investigators in Russia reportedly are using foliar sprays in an effort to help overcome low soil temperatures.

There has been some publicity given to the use of small amounts of complete fertilizers sprayed on the above-ground portion of plants. Mederski and Volk (1956) point out that the amount of nutrients furnished by a few gallons of 5–10–5 sprayed on the foliage of corn, sugar beets, soybeans, oats, alfalfa, and wheat did not significantly affect yields.

V. Time of Application and Residual Value of Fertilizers

As larger and larger amounts of nutrients are applied in order to reach top profits, additional problems arise in respect to time of application. Likewise, these larger amounts affect the consideration which must be given to residual effects. Formerly, with the low rates of application used, little residual effect was anticipated from fertilizer.

The Subcommittee on Economics of Fertilizer Use of the North Central Farm Management Research Committee (1954) states that optimum application of fertilizer for corn on a one-year basis contributes substantially to succeeding crops. If residual effect is also considered in estimating the most profitable level of application of fertilizer to corn, the optimum level is higher than it would be on a one-year basis.

A. Nitrogen

1. *Residual Value of Applied Nitrogen*

Long-time studies on nitrogen accumulation in soils have centered attention on the efficacy of legumes in providing the nitrogen for succeeding crops in the rotation and in maintaining or enhancing the organic nitrogen reserves (Ensminger and Pearson, 1950). Large-scale use of commercial synthetic nitrogen fertilizers began only recently. This development gave rise to questions which agronomists were unprepared to answer, since legumes had for so long occupied a focal point in the nitrogen economy.

The benefits to be derived from applying large amounts of nitrogen fertilizers to such crops as corn, cotton, and small grains are now well recognized. From an economic standpoint, continued use of nitrogen at profitable levels demands that adjustments of fertilizer recommendations be made where residual accumulations occur. From a large number of 2- to 3-year experiments conducted in Iowa (Dumenil and Nicholson, 1952), it was learned that when substantial amounts of nitrogen were applied to corn some may carry over to the succeeding crop. For example, it was observed that 40 to 60 lb. of nitrogen per acre plowed under for corn gave a residual effect on the oats following which was equivalent to about 20 lb. of newly applied nitrogen. Substantial carryover also occurred in Missouri experiments (Smith *et al.*, 1955).

Pumphrey and Harris (1955) likewise showed that nitrogen applied on corn under irrigation gave considerable residual effect on corn the next year (Fig. 14). The value of the increased yield of corn the second year was sufficient to pay the entire cost of the nitrogen. In most cases the cost of fertilization is charged to the crop treated. It is apparent that if we are to make a critical economic evaluation of fertilizer use the carryover value must be considered.

2. *Factors Affecting Retention*

Recently, there has been renewed interest in the problem of nitrogen loss by volatilization. Investigators in Missouri (Wagner and Smith, 1957) and Wisconsin (Loewenstein *et al.*, 1957) have reported losses of applied nitrogen fertilizer in gaseous form as great as 50 per cent or even higher in certain instances on a wide range of soils. Such losses involve volatilization of ammonia, conversion of nitrate to gaseous oxides of nitrogen, and perhaps some elemental nitrogen. Such striking results will be likely to stimulate renewed effort in ascertaining the soil and environmental conditions which determine the extent of loss. Oxygen supply, nature and quantity of organic matter, and moisture level influence de-

nitrification processes. Broadbent (1951) considers that denitrification may occur in normally aerated soils. Bremner and Shaw (1956), however, raise some question on this point, since they were unable to detect nitrogen loss with a plentiful oxygen supply.

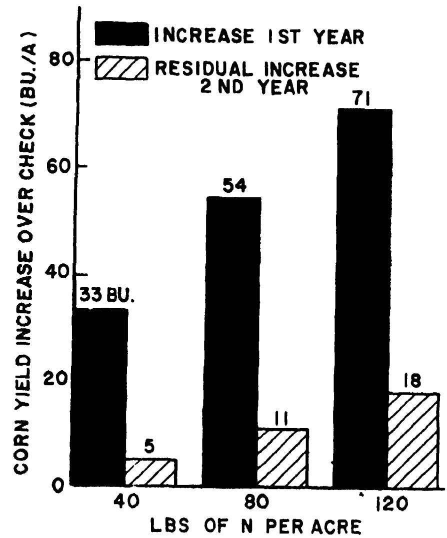


FIG. 14. Residual effect of nitrogen on corn yields the year after application was substantial on this irrigated soil. The yield increase the second year would approximately pay for the entire cost of the nitrogen (Pumphrey and Harris, 1955).

The view is held by some that the soil organic matter supply, and hence residual nitrogen, is augmented by applying nitrogen to incorporated carbonaceous residues. It has been claimed that nitrogen application aids in conserving the carbon of such residues and, hence, results in faster buildup of soil organic matter. Such a view is misleading and disregards the fact that loss of carbon dioxide is a necessary consequence of decomposition, as pointed out by Allison (1955). The effect of nitrogen is mainly a result of the larger crop growth produced by fertilization (i.e., larger crop yields, more residues, more organic matter).

The factors affecting nitrogen carryover from year to year under various soil and climatic conditions are only partly understood. Chemical nature of the residual nitrogen is important. That present as nitrate is free to leach and, as pointed out by Nelson and Uhland (1955), its retention in

the soil zone accessible to roots is determined by extent of water percolation through the soil profile. Soil texture affects water retention and, hence, percolation losses. Cooke and Cunningham (1956) observed that nitrate is not easily leached out of heavy soils with good structure, even with average summer rainfall, and suggest that nitrate ions may be retained inside structural aggregates not readily susceptible to leaching.

A portion of the ammonium form becomes fixed by types of clay minerals known to be present in certain soils much the same as is potassium. The nitrogen thus fixed is released very slowly. Hanway *et al.* (1957) found that potassium tends to block this release. Whether or not ammonium fixation is of practical importance in influencing efficiency of applied nitrogen is yet to be learned (Allison *et al.*, 1953).

Satisfactory means of measuring the residual nitrogen in soils as a basis for predicting subsequent applications have not been devised. Empirical relations between nitrate release values determined on surface soils and crop response to nitrogen fertilization (Fitts *et al.*, 1955; Hanway and Dumenil, 1955), while useful in assessing the relative nitrogen status of soils subjected to comparable prior fertilizer treatment and management, fail to measure residual nitrogen from recent applications.

3. *Time and Frequency of Application*

There is considerable interest in evaluating the practices of fall and spring application of nitrogen for spring-seeded crops. Nelson and Uhland (1955) call attention to the major factors which influence losses of fall-applied nitrogen. Chief among these are temperature, amount and distribution of rainfall, evapo-transpiration rate, and soil profile characteristics. Based on these considerations, the Eastern and Plains states were broadly divided into four areas representing different degrees of susceptibility to leaching (Fig. 15). In Area I, fall applications would involve little risk for corn or small grain, as is further indicated by data in South Dakota and Nebraska (Lamke *et al.*, 1957). In Area II (Fig. 15) where susceptibility to leaching is greater, it is advisable to delay the fall application until soil temperature is low enough to appreciably retard rate of conversion from ammonium to the nitrate form of nitrogen. In Areas III and IV, feasibility of fall application must be regarded as being questionable, according to Nelson and Uhland (1955). Of course some nitrogen application to fall-seeded crops, such as wheat and oats, in the latter two areas is desirable. In many instances, supplemental applications are made the following spring rather than attempting to supply the total needs at time of seeding. As might be expected in Area IV, excess nitrogen which is not taken up by the crop during fall growth may be largely lost from

the soil by the time growth is resumed. Based on Missouri studies on fall-seeded small grain, equal effects from nitrogen application may be expected any time from preplanting to early spring, except on sandy soils (Smith *et al.*, 1955).

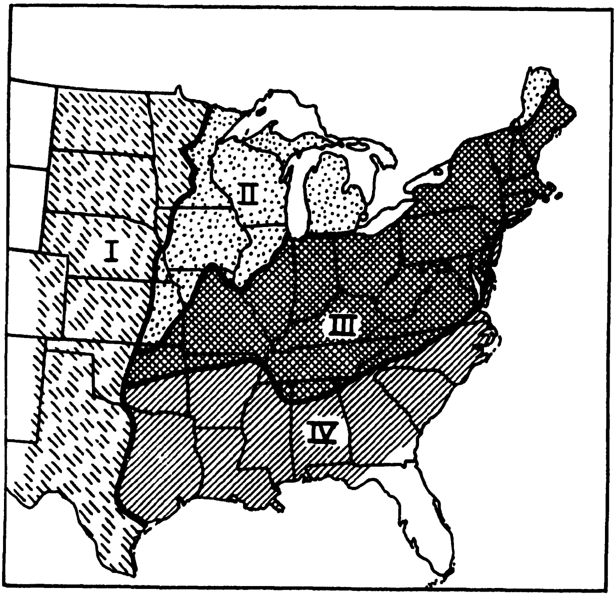


FIG. 15. Relation of degree of leaching to geographic area. Leaching ranges from nil in Area I to very high in Area IV (Nelson and Uhland, 1955).

Finney *et al.* (1957) reported that foliar application of urea in several sprayings, supplying 10 to 50 lb. nitrogen per acre, increased wheat yields when applied up to 21 days before flowering. After this time only the protein content was increased. The results were very striking, particularly when urea was sprayed at flowering time.

A few years ago there was much emphasis on sidedressing corn. Subsequent experimentation, for example work by Krantz and Chandler (1954), has shown that on all except the lightest textured soils preplant application is fully as effective as sidedressing (Fig. 16). This gives much leeway in the time of nitrogen application and hence this fits in well with custom application and peak labor demands. Late sidedressing of corn or cotton is frequently found to be as effective as preplanting application if moisture conditions are favorable for immediate transfer to the root zone.

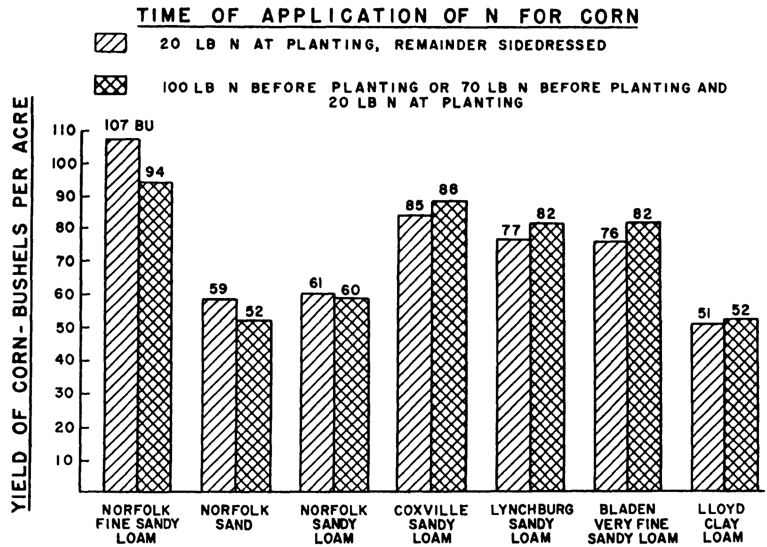


FIG. 16. Except on the lighter textured soils preplanting application is fully as effective as sidedressing (Krantz and Chandler, 1954).

B. PHOSPHORUS

1. *Behavior of Applied Phosphorus and Residual Effects*

The fact that plants obtain much of the applied phosphorus from the soil-fertilizer reaction products has prompted many studies to determine the nature of the reactions which occur. It has been demonstrated repeatedly that the initial phases of phosphorus reversion occur rapidly when soils are contacted by dissolved fertilizer. With further time of soil-fertilizer contact, the rates at which intermediate reaction products alter to more stable and less soluble compounds become of importance in determining plant uptake of phosphorus. A knowledge of soil characteristics as they affect the nature and rate of soil-phosphorus reactions is basic to an understanding of residual phosphorus and its availability to plants.

a. Calcareous and inherently neutral soils. Early workers with calcareous soils concluded that phosphorus was present largely in sparingly-soluble apatite compounds. The presence of calcium carbonate was considered to exert a further repressive effect on solubility of phosphate compounds. A prevalent view was that applied soluble phosphorus fertilizers soon reverted to highly unavailable basic calcium phosphates. Recent findings

(Hagen and Hopkins, 1955) illustrate the decreased availability of the phosphorus associated with a high $HPO_4^{--}:H_2PO_4^-$ ion ratio in the soil solution at high pH. The literature on behavior of phosphorus in calcareous and alkaline soils has been reviewed recently by Olsen (1953).

The fundamental investigations of Olsen (1953) and Olsen and Watanabe (1957) on factors which control plant availability of phosphorus in calcareous soils of the Western states have clearly established the relation of surface-active phosphate ions in the soil system to plant availability.

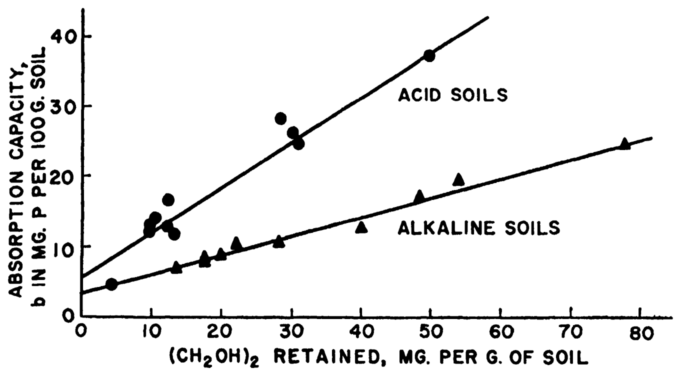


FIG. 17. Phosphorus adsorption maximum, b, from the Langmuir equation versus relative surface area (glycerol retention method) for acid and alkaline soils (Watanabe *et al.*, 1957).

This fraction of soil phosphorus which readily equilibrates with radioactive phosphorus is relatively available to plants. Further, Olsen and Watanabe (1957) found that the adsorption capacity (b) for phosphorus in calcareous soils, calculated from the Langmuir equation, was linearly related to surface area of soils as measured by glycerol (Fig. 17). A somewhat poorer relation was found for acid soils. The degree of saturation

$$\frac{\text{surface P}}{\text{adsorption capacity}}$$

was found to be correlated with phosphorus uptake by plants (Watanabe *et al.*, 1957) (Table XII).

Little direct evidence has been reported concerning the nature and availability of that portion of the applied phosphorus which reverts to forms not readily exchangeable with P^{32}. Recent evidence has been obtained, however, regarding certain reactions which calcium phosphates undergo at the site of application. When pellets of monocalcium phosphate monohydrate, $Ca(H_2PO_4)_2 \cdot H_2O$, were placed in calcareous soil, or in acid

TABLE XII

Phosphorus Uptake from Residual Forms in Relation to Per Cent Saturation (Watanabe *et al.*, 1957)

Soil no.	Adsorption maximum (mg. P/100 g. soil)	Per cent saturation	P uptake (mg. per pot)
348	24.6	13.9	1.9
351	19.5	18.5	3.6
330	17.1	20.7	5.3
333	12.7	24.4	10.0
345	10.5	28.2	12.8

soil, the residue remaining at the pellet site after several days consisted usually of dicalcium phosphate dihydrate, $CaHPO_4 \cdot 2H_2O$, and occasionally anhydrous dicalcium phosphate (Brown and Lehr, 1959). In calcareous soils or heavily limed acid soils, band applications of −35 mesh monocalcium phosphate and dicalcium phosphate dihydrate reverted largely to octocalcium phosphate, $Ca_4H(PO_4)_3 \cdot 3H_2O$, and, in one instance, to an apatite during a 3-month period of cropping (Terman *et al.*, 1958; Lehr and Brown, 1958). However, the anhydrous dicalcium phosphate crystals had undergone no surface erosion or apparent physical or chemical alteration. The release of phosphoric acid which accompanied the alteration to more basic octocalcium phosphate conceivably contributed to phosphorus nutrition of the plant.

Direct evidence has not been obtained regarding the reaction products formed in the soil mass upon application of water-soluble phosphorus compounds such as phosphoric acid and the ammonium phosphates. Too, much is yet to be learned about specific reactions of dissolved superphosphate in high pH soils. The precipitated reaction products evidently occur as very finely divided particles having large surface area (Olsen, 1953).

Published results rather consistently reveal substantial residual effects of phosphorus fertilizers applied to calcareous soils. Such evidence is found in reviews by Olsen (1953) and Stanford and Pierre (1953). In more recent studies, Schmehl *et al.* (1955) and Webb and Pesek (1954), Stanberry *et al.* (1955), and Haddock and Linton (1957) have all reported residual effects lasting from two to four years following moderate to heavy applications. Olsen (1953) and Olsen *et al.* (1954b) observed a close linear relationship between "A" values (Fried and Dean, 1952) and surface-active phosphate in long-time rotation-fertilization plots. When "A" values were expressed as percentages of total accumulated (residual) phos-

phorus, values were as follows: Ft. Collins loam, 26–30 per cent; Pryor silty clay loam, 15–38 per cent; Tripp very fine sandy loam, 44–56 per cent. In these studies, "A" values and amounts surface-active were of the same magnitude. On the other hand, less than 3 per cent of the total phosphorus in unfertilized soils was present as surface phosphorus (Olsen, 1953).

Of considerable practical importance is that an accumulation of residual surface phosphorus, corresponding approximately to 20 per cent of the adsorption capacity, is near adequate for growth of crops (Watanabe *et al.*, 1957). A measurement of per cent saturation, therefore, holds some promise as a quantitative basis for calculating the amount of phosphorus fertilizer required to achieve the desired level of saturation. In practice, the phosphorus extractable in a 0.5 *M* solution of $NaHCO_3$ at pH 8.5, which correlates well with surface phosphorus, is a useful test for predicting phosphorus needs of calcareous soils (Olsen *et al.*, 1954b).

Relative efficiency of phosphorus residues may be a function of soil type, soil texture, calcium carbonate content, and particularly the level of available phosphorus present in the soil prior to fertilizer application (Olsen *et al.*, 1954a).

b. Acid and limed acid soils. Kurtz (1953) in reviewing present concepts of phosphorus behavior and the nature of soil-phosphorus reaction products in acid soils emphasizes surface adsorption as a general mechanism of phosphorus retention. He points out the problems inherent in establishing suitable criteria for distinguishing between surface-adsorbed and precipitated forms of phosphorus in the soil system. Kittrick and Jackson (1956) in a comprehensive evaluation of the nature of phosphate fixation consider that chemical bonding or crystallization accounts for initial and subsequent phases of precipitation. Crystal growth, accompanied by a decrease in number of readily accessible phosphate ions, accounts for the slow decline in availability of applied phosphorus.

Mattingly (1957) states that while "the total quantity of labile phosphorus in soil has been successfully determined by radiochemical methods, so far little progress has been made in establishing either the chemical form, or, therefore, in showing what forms of inorganic phosphorus contribute most to nutrition of crops in soil." He predicts that "increasing attention will be given during the next few years to the relationship between phosphate concentration and the labile phosphate in soils, and to the *rate* of release of phosphate from the solid phase of both soils and fertilizer into the soil solution." In this regard, studies reported by Fried and Shapiro (1956) are of particular interest.

Pellets or bands of superphosphate or dicalcium phosphate in limed acid soils behaved much the same as in calcareous soils as mentioned

earlier (Section V, B, 1, a), while in unlimed acid soils there was no evidence of octocalcium phosphate as a residue. An immediate problem, of course, is to determine the contribution of the residues to phosphorus nutrition of the plants. Moreover, a knowledge of the composition of the residues should assist the chemist in deducing the composition of the solution which emerges from the pellet or band (Brown and Lehr, 1959). Such information provides the basis for a fresh approach to studies of phosphorus reactions with soils, clays, and other soil constituents. Lindsay and Stephenson (1959) have shown, for example, that the solution in equilibrium with monocalcium phosphate and anhydrous or hydrated dicalcium phosphate (approximate pH range 1 to 1.5), dissolves large amounts of iron and aluminum from soils. Phosphorus compounds evidently precipitate as the pH of the system is increased.

These observations help to emphasize the need for continued investigations on the behavior of applied fertilizer phosphorus in order better to predict direct and residual effects. Meanwhile, empirical procedures are being used to practical advantage in assessing the residual value of previous applications and in predicting need for additional fertilization. Soil tests for phosphorus are widely used (Nelson *et al.*, 1953).

Reference to the residual effects of applied phosphorus fertilizers in acid soils is found in a recent monograph (Pierre and Norman, 1953). Subsequently, a number of investigations on accumulation and availability of phosphate residues in acid soils have been published.

In several more recent studies, relative phosphorus availability resulting from prior applications has been assessed by using P^{32} to determine "A" values. The A-value denotes the quantity of available soil phosphorus possessing an availability equivalent to that of the applied radioactive source of phosphorus. Usually superphosphate or resin-adsorbed phosphorus has been used as the standard tagged source. Caldwell *et al.* (1956) found, at the end of a six-year period during which 40 lb. P_2O_5 per acre had been applied annually, that A-values accounted for 1/5, 1/4, and 1/3 of the total application, respectively, as measured by uptake of wheat, legume, and corn.

Prince (1953), using red clover in pot experiments, determined increases in A-values which were less than 10 per cent of the phosphorus applications made over a 36-year period to soil of pH 5.5. Additions to a cotton-corn-oats rotation ranged from 720 to 4320 lb. P_2O_5 per acre. Assuming that these crops removed about 720 lb. P_2O_5 in thirty-six years and that 10 per cent or 72 lb. was derived from fertilizer, it appears that upwards of 80 per cent of the fertilizer applied had reverted to forms not available, using A-value as the criterion. Similarly, Stelly and Morris (1953) found evidence of very low residual value from 250 to 5000 lb. per

acre of superphosphate applied in 1949 to a Cecil soil and cropped in 1951. Liming improved the residual value. Rubins (1953) observed that A-values of six potato soils which had been heavily fertilized reflected the relative amounts of phosphorus taken up by several crops in the greenhouse.

Smith (1957), using oats as the test crop, determined that the effectiveness of applications made one to two years previously, relative to current applications of superphosphate, was relatively high. Expressed as the percentage of current application, values were: Floyd soil, 55 to 57 per cent; Edina soil, 68 to 75 per cent; Ida soil, 65 to 75 per cent. On the same basis, effectiveness of three-year-old applications ranged from 20 to 40 (current application = 100).

Moore *et al.* (1957) found that the recovery of applied phosphorus by 11 crops of oats ranged from 51 to 72 per cent. Recovery by the first crop was less than 20 per cent from the silt loams and about 35 per cent from the sand.

In the studies cited above, A-values generally correlated well with one or more chemical extraction procedures. Such observations have been of great value, therefore, in lending support to the validity of certain soil tests. In calcareous soils, for example, the correlation coefficient (r) was about 0.95 relating A-value to surface, $NaHCO_3$-soluble, Bray No. 1 (dilute acid-fluoride), and water-soluble phosphorus (Olsen *et al.*, 1954b). Similarly, on acid soils, A-values by Caldwell *et al.* (1956) and Prince (1953) correlated well with ammonium fluoride-extractable phosphorus. Where various phosphorus sources were studied, Ensminger and Pearson (1957) found certain marked discrepancies in the relation of yield or extractable phosphorus to A-values, attributable in part to source effects other than phosphorus. Rubins (1953) found the decline in A-values due to cropping to be about equal to the loss in NaOH-extractable phosphorus. In Smith's (1957) studies, the Bray No. 1 test (0.025 N HCl – 0.03 N NH_4F) predicted A-values equally well for one- and two-year-old applications to Floyd and Edina soils, and a single linear regression adequately described the relationship.

Recent studies of Hutton *et al.* (1956), Robertson *et al.* (1956), Cheaney *et al.* (1956), and Smith (1957) exemplify current interest in predicting the rate of phosphorus application necessary to achieve the desired fertility level in soil. An experiment reported in two related papers by Hutton *et al.* (1956) and Robertson *et al.* (1956) consists of a $5 \times 5 \times 5$ nitrogen-phosphorus-potassium factorial combination in a 2-year corn-peanut rotation intercropped with oats and lupine. Data in Fig. 18 (Hutton *et al.*, 1956) show a gradual buildup of acid-extractable soil phosphorus from four successive annual applications made in 1950, 1951, 1952,

and 1953. Samples were taken prior to the next fertilization. Corresponding yield curves are shown in Fig. 19, together with calculated amounts of nutrient giving maximum yields. Due to adverse conditions in 1952 and 1954, yield responses were nil or yield depression occurred due to the

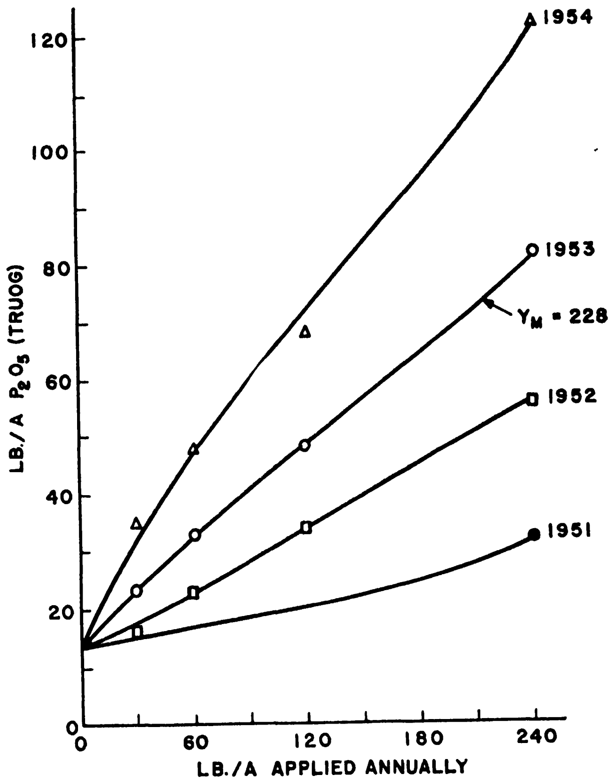


FIG. 18. Effect of phosphorus application to Red Bay fine sandy loam on the amount extracted by the Truog procedure (Hutton *et al.*, 1956).

fertilization. Such lack of balance between available moisture and nutrient supply, resulting in poor crop yields, complicates the evaluation of direct and residual effects of nutrients. Yet, the occurrences cannot be disregarded and, in practice, affect decisions as to rates of nutrient application for the succeeding crop.

Dumenil *et al.* (1954) suggest that the amount of phosphate fertilizer carried over in a readily available form varies more with the kind of soil

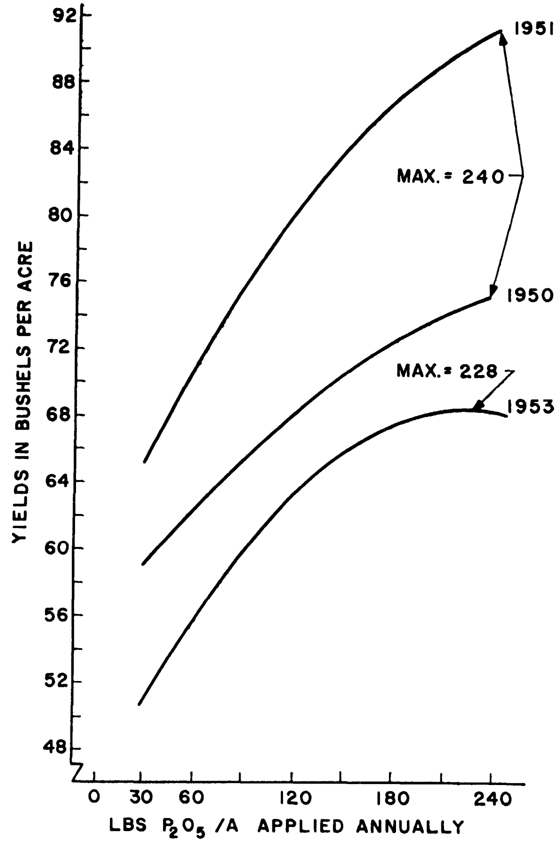


FIG. 19. Corn yield responses to phosphorus and amounts required for maximum yield (Hutton *et al.*, 1956).

and the amount applied than with the kind of crop grown. On well limed soils with 40 pounds P_2O_5 applied about 40 per cent may remain. With applications of 80 pounds P_2O_5, the carryover may amount to 60 per cent.

The British have long been interested in a system for calculating compensation for fertility left after fertilization. Watson (1946) presented the joint thinking of prominent agricultural scientists in Great Britain (Table XIII).

2. *Loss of Applied Phosphorus Fertilizer*

Luxury consumption of phosphorus by plants is not generally regarded as a problem. Occasionally, however, data of the kind reported by Chea-

TABLE XIII

Annual Compensation for Fertility Left After Fertilization (Watson, 1946)

	Amount to be compensated for		
	After 1st year	After 2nd year	After 3rd year
Phosphorus	⅔	⅓	⅙
Potassium	½	¼	—

ney *et al.* (1956) reveal that large applications may actually provide more than adequate amounts of phosphorus to plants. In this study, near maximum yield was achieved by applying 60 lb. P_2O_5 every two years resulting in an average phosphorus content of forage of 0.44 per cent. Yields were not significantly greater with 120 and 240 lb. P_2O_5 per acre, but average phosphorus contents were 0.57 and 0.69 per cent, respectively. These values are well above the levels required for adequate growth of forages. Biennial application resulted in removal of about one-half as much phosphorus as the heavier application.

Erosion accounted for appreciable loss of phosphorus in studies reported by Ensminger (1952). Where 750 to 2300 lb. P_2O_5 per acre had been applied to a Hartsells fine sandy loam over a sixteen-year period, the average loss was 40 per cent under a corn-cotton (winter legume intercrop) rotation and 63 per cent under corn-cotton rotation. A striking feature of these results is that the soil was nearly level (2–4 per cent slope).

Ensminger (1952) explained the losses as being due to clay removal from the plots, sheet erosion of coarser soil fractions, and washing away of partially decomposed crop residues. Where soil is susceptible to erosion, it appears, therefore, that inefficient use of applied phosphorus over a period of years may be attributed not only to chemical reversion but also to erosion losses of appreciable magnitude. Ensminger concluded that for cultivated crops only the amount of phosphorus needed for the immediate crop should be applied, and that the soil may not be as safe a place to store surplus phosphorus as the fertilizer bag.

Leaching losses of phosphorus are negligible in most soils. However, as reported by Neller and Bartlett (1957), leaching may occur in certain sandy soils of Florida having low phosphorus-fixing capacity. In such instances, moderate liming retards leaching. These workers consider the problem to be of some practical significance, and have investigated the possibility of using sparingly soluble phosphorus compounds instead of the water-soluble carriers to minimize the leaching effect.

3. *Time or Frequency of Application*

The interactions of application rate and placement on the effects of time or frequency of phosphorus application complicate evaluation of the latter two factors. Using heavy rates, less frequent application is needed on many soils and for certain crops. In some instances, the single rate required may be excessive, however. For example, Cheaney *et al.* (1956) obtained total maximum forage yields during a four-year period on a clay loam soil from initial applications of 240 to 480 lb. P_2O_5 per acre as superphosphate. About 90 per cent of maximum yield resulted from applying 60 lb. P_2O_5 every two years. On the other hand, a single initial application of 120 pounds P_2O_5 gave only 70 per cent of maximum yield. Thirty pounds P_2O_5 applied annually for four years was sufficient to give 80 per cent of the yield obtained from 480 lb. applied initially. Based on this four- year study, it appears that frequent moderate application was a better alternative than infrequent heavy application. Similarly, Wakefield *et al.* (1957) found that 30 lb. P_2O_5 applied annually or 60 lb. applied biennially was much more efficient than a single initial application for Ladino clover.

Stanford *et al.* (1955) concluded that 80 pounds P_2O_5 applied initially on a red clover-timothy-alfalfa seeding was less efficient than 40 lb. P_2O_5 applied both at seeding and topdressed the second year. Schaller and Pohlman (1955), however, found no difference in yield of permanent pastures on proportion of desirable species associated with various frequencies of superphosphate application, e.g., 100 lb. annually, 200 lb. biennially, 400 lb. quadrennially, and a single 800 lb. initial rate.

Application of phosphorus to each crop permits taking advantage of the increased efficiency resulting from localized placement. This is exemplified in numerous studies which have demonstrated the superiority of band placement over broadcasting for small grains and cultivated row crops, particularly on acid soils.

The need for annual application differs among crops and soils. Terman *et al.* (1952) and Struchtemeyer *et al.* (1955) observed that annual row side-band application of 80 to 100 lb. P_2O_5 per acre for potatoes frequently gave good responses, even on high-phosphorus soils. Similarly, many farmers of the Corn Belt practice annual placement of row fertilizer for corn as a supplement to heavier, less frequent application. Benefits of small, localized starter applications of phosphorus, especially when combined with nitrogen, have been amply demonstrated with various crops (Fine, 1955). Topdressing of meadows and pastures fortunately results in effective use of phosphorus under most farming conditions, thus giving a very suitable alternative to heavy initial application. Indeed, annual topdressing often is superior to single initial application on meadows.

Barber (1958) concluded that the soil test can be used to predict the amount by which the available phosphorus is increased by phosphate applications. Bronson and Barber (1957) state however that for maximum yields in Indiana the soil should be built up to 180 lb. of P_2O_5. Table XIV shows the approximate amounts required to attain this.

TABLE XIV

Approximate Amounts of P_2O_5 Needed to Raise Soil Test to 180 in ndiana Soil

Present soil test	P_2O_5 required, lb./A.
0–25	400
26–50	300
51–75	225
76–100	150
101–125	90
126–150	50

The above amounts can be applied all at once for rapid build up or split into several applications for gradual build up. This is applied in addition to amounts needed to maintain soil test levels. For good yields in a corn-soybean-wheat-hay rotation about 150 lb. of P_2O_5 per acre for the four years is suggested for maintenance. This would be applied at time of planting of corn and wheat and possibly as a topdressing on the hay.

Fall application of phosphorus fertilizer for crops to be sown in the spring is coming to be a widely accepted practice (Nelson and Uhland, 1955). The initial rapidity of phosphorus reversion and subsequent slow decline in availability may account for the relatively small differences in availability often observed in comparing response to application at planting and several weeks or a few months prior to planting. Much reversion has occurred before plants are capable of utilizing appreciable phosphorus in either case. Olson and Dreier (1956a) noted about 20 per cent less uptake of phosphorus by oats due to mixing 40 lb. soluble P_2O_5 with soil two months in advance of seeding as compared to application at seeding. Here, not only was there reduced availability due to reversion but also the advantage of specific placement for the crops, such as drilling with seed and intimate association of phosphorus and nitrogen, was lost by preplanting application. Moreover, the possibility of erosion loss on fallow ground should not be disregarded (Ensminger, 1952) in preplanting applications.

C. Potassium

1. *Residual Value of Applied Potassium*

There is much evidence that an application of potassium has carryover effects in succeeding years. This is shown by increased crop yields and uptake of potassium and on many soils a higher potassium soil test. Dumenil *et al.* (1954) state that the carryover effect of potash varies not only with the soil but also with the crop grown and how it is handled. Applied to corn carryover is about 60 per cent if the stover is left and 30 per cent if stover is removed. On top-dressed legume hay carryover is not more than 25 per cent.

Unfortunately on some soils it is not possible to show increased level of potassium in the soil by analysis as the potassium may go into the nonexchangeable form. In this position it may not be extracted by the usual rapid extraction procedure employed in analyses, but may be gradually made available to plant roots.

Understanding of the soil constituents responsible for potassium fixation and the nature of fixation and release has progressed significantly during the past two decades. Most soil scientists now regard fixation as being essentially a cation exchange phenomenon. Entrance of potassium ions into interlayer lattice positions where they become fixed is accompanied by a replacement of equivalent amounts of calcium, magnesium, sodium, hydronium, aluminum, or other cations. Where calcium, magnesium, and sodium predominate, the exchange occurs readily. Ionic forms and hydroxides of aluminum and iron and hydronium ions tend to block fixation (van der Marel, 1954). Ammonium ions are particularly effective in this regard, since they, too, become fixed.

Release of potassium from the mica-like clay minerals also is dependent upon the cationic environment. Thus, Hanway *et al.* (1957) demonstrated that release of fixed potassium or ammonium is blocked by relatively low concentrations of these same ions present in the outer solution. Release is facilitated, however, by increasing the ratio of nonfixable to fixable cations. Continued research along these lines gives promise of further clarification of the factors which govern the rate of potassium release.

Recently there has been renewed interest in the practical implications of soil drying on potassium release. Luebs *et al.* (1956) demonstrated that the potassium released from several soils upon air-drying resulted in increased uptake of this nutrient by plants, as is evident in Fig. 20. In this study, a portion of each soil taken from the field was not allowed to undergo further desiccation before application of potassium fertilizer and cropping. Additional lots of soil were air-dried and cropped without ap-

plying potassium. The latter treatment is represented by a large circle on each yield-of-potassium line. Vertical projections show that potassium release on drying corresponded to application of 15 to 120 lb. potassium per acre. Under actual field conditions the effect of drying on potassium release was evident only in the surface inch layer of soil, which suggests that drying may be of minor consequence in releasing potassium for plant consumption during a growing season. It also appears unlikely that fixation of potassium by expanding lattice minerals of the montmorillonite type, often demonstrated in the laboratory, is of importance under field conditions.

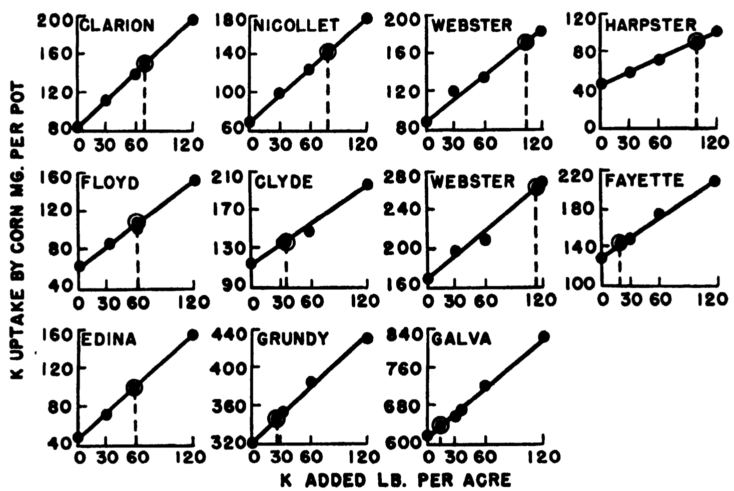


FIG. 20. Uptake of potassium from undried soils as affected by rate of application and by air-drying the unfertilized soil (vertical dashed line) (Luebs *et al.*, 1956).

DeTurk *et al.* (1943) concluded that "potassium fixation in corn belt soils has merits which counterbalance in considerable measure its recognized disadvantages." Nothing has come to light in subsequent studies seriously to challenge this general viewpoint. Aside from investigations by van der Marel (1954) further study seldom has revealed instances where fixation clearly was associated with inefficient use of applied potassium. In this regard, reference to Fig. 20 is of further interest. It is doubtful if the linear relation between yield-of-potassium and rate of application would have obtained had fixation exerted a dominant influence. Moreover, on ten of the soils (excluding the Harpster) recovery of applied potassium ranged from approximately 75 per cent to almost 100 per cent. The rela-

tively low recovery (approximately 50 per cent) from the Harpster silty clay loam soil may be attributed to the unusually large capacity of this soil to fix potassium under moist conditions.

Attoe (1949) grew seven successive crops of oats on potassium-fertilized soils and recovered from 76 to 98 per cent of the applied potassium. Even in instances where laboratory determinations indicated 56 per cent fixation of applied potassium, recovery by oats exceeded 90 per cent. In Iowa studies (Hanway *et al.*, 1953) apparent recovery of top-dressed KCl (60 and 120 lb. K_2O per acre) during two seasons by alfalfa-timothy meadow ranged from about 75 to 100 per cent. These and other studies show that potassium fixation does not adversely influence potassium utilization under a wide range of soil conditions.

Losses of potassium by leaching have been greatly overemphasized except on very sandy soils. Stauffer (1953) determined the losses from several Illinois soils over a ten-year period. On an annual basis the soils lost about 2 lb. of K per acre. One of the merits of fixation is the protection which it gives against leaching losses. The potassium held in exchangeable form leaches slowly, as is evidenced by studies of DeTurk *et al.* (1943), involving application of one ton of KCl or KH_2PO_4 per acre. Under more extreme leaching conditions in Mississippi, Hoover (1944) found evidence that relatively little of the applied potassium had leached from the A to the B horizon of several soils. Exchange capacities of soils included in this study generally ranged from 3 to 7 milliequivalents (meq.) in the surface layers, and from 5 to 10 meq. in subsurface layers. On the other hand, in Florida, Robertson *et al.* (1956) found little evidence of a residual accumulation of exchangeable potassium applied as KCl to a Red Bay fine sandy loam following five annual applications of 15 to 120 lb. K_2O per acre. This was further evidenced by the fact that no significant change occurred during the five-year period in the quantity of potassium required to give maximum corn yields.

2. *Time and Frequency of Application*

Efficiency of potassium fertilizer use commonly is considered to be a function of plant characteristics and of soil characteristics which govern, for example, fixation and leaching losses.

Uptake of potassium by the plant has been studied in relation to competition with other cations, aeration, competition of plant species for available potassium supply, and other factors. Luxury consumption of potassium by certain plants often has been demonstrated. Although a level of 2 per cent potassium in plant vegetation (air dry basis) commonly is considered to represent an adequate level for near maximum growth, 3 to 5 per cent or higher may be reached with excessive fertilizer appli-

cation. Perhaps too much emphasis has been placed upon the practical importance of luxury feeding. It is of greatest significance on light textured soils where the above ground part of the plant is harvested. The problem usually encountered is that of supplying adequate quantities of potassium, particularly in cropping systems where much of the dry matter produced is removed (Brown, 1957). Grasses, legumes, silage corn, and cereal straw remove large quantities of potassium, whereas most grains (exception, soybeans) remove relatively little.

Luxury consumption is indeed a problem if an attempt were made, for example, to supply at once the total potassium requirement of a grass-legume meadow to be left down for several years (Brown, 1957). On potassium-deficient soils, it is generally considered that annual application to long-time meadows or pastures and to crops in the rotation is more effective than infrequent, heavy application. Where two or more harvests are made annually, as with forages, the requirement for potassium may best be met by top-dressing between cuttings at least once during the season.

An illustration of the combination of broadcast and row application of fertilizer, below, is taken from Purdue recommendations on a soil testing low in phosphorus and potassium for a corn-soybean-wheat-hay rotation (155 lb. P_2O_5 and 235 lb. K_2O needed in the rotation).

TABLE XV

Purdue Recommendations on Soils Testing Low in Phosphorus and Potassium

Corn	0 + 90 + 180	broadcast (N as needed)
	5 + 20 + 20	in row
Soybeans	No fertilizer	
Wheat	10 + 40 + 40	in row (N as needed)
Hay	No fertilizer	

In this system the bulk of the potassium is placed as far away from the hay crop as possible.

Illinois recommendations suggest maintaining the supply of potassium by broadcast applications once or twice in the rotation. Purdue recommendations state that row applications are not necessary if sufficient potash is broadcast, unless the soil test is low.

On potassium deficient soils, particular difficulty may be encountered in satisfying the potassium requirements of grass-legume associations. The grass is better able to compete for the soil potassium and contains appreciably more potassium than the legume as shown by Gray *et al.* (1953),

Parsons *et al.* (1953), Hanway *et al.* (1953), and Blaser and Brady (1953) (Fig. 21). The legume stand is adversely affected by such competition, and encroachment of weedy grasses accentuates the difficulty of maintaining the legume. Frequent application of potassium offers a practical solution in increasing longevity of the legume in many instances (Brown, 1957). However, certain legume-grass mixtures, such as Ladino clover-bentgrass, were incompatible in that it was virtually impossible to supply enough potassium to maintain the Ladino clover (Gray *et al.*, 1953).

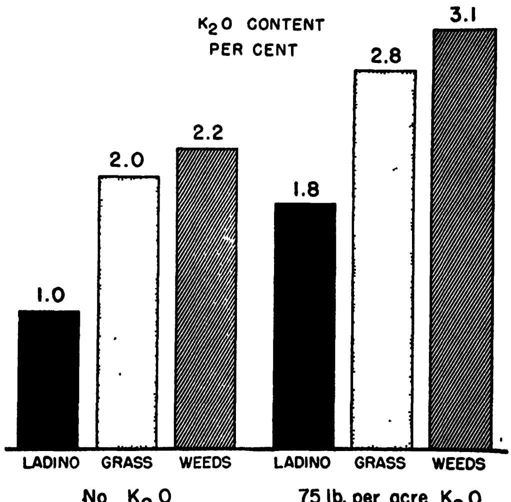


FIG. 21. Grasses and weeds are better able to take up potassium from the soil than are legumes. Under low potassium conditions legumes tend to disappear from forage mixtures (Blaser and Brady, 1953).

VI. Lime Level and Response to Fertilizers

Use of limestone in United States reached its peak in 1947, began a downward trend reaching a low in 1954, and then started to climb. Lime usage now is about 25 per cent of optimum. Lack of lime is undoubtedly one of the important factors limiting responses to nitrogen, phosphorus and potassium. Agricultural leaders are recognizing that optimum yields of even non-legumes require a properly limed soil as high yields are attempted.

An example of meeting the needs of soybeans for lime, phosphorus, and potassium on nine Coastal Plain Soils is shown in Fig. 22. Under the con-

ditions of these experiments all three were required for top returns. Lime alone or 0–10–20 alone returned only $7 per acre above cost. Together the return was $26.

A basic fact important to keep in mind is that as liming increases yields there will be a greater drain on the nutrient supply in the soil.

Brief mention will be made as to relationships with nitrogen, phosphorus, potassium, and magnesium. Lime has a marked effect on availability of minor elements but this aspect will not be covered.

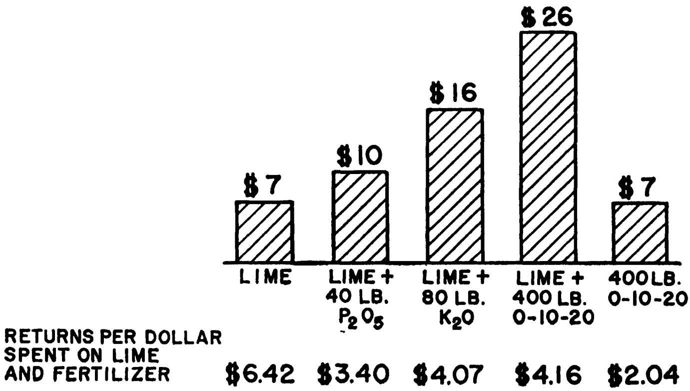


FIG. 22. Soybeans needed lime, phosphorus, and potassium on these soils. Average of results on nine experiments in the Coastal Plain (Nelson, 1953).

A. NITROGEN

Higher rates of nitrogen increase the rapidity of lime losses from the soil. This serves to focus greater attention on the need for lime.

The synthetic nitrogen sources such as anhydrous ammonia, ammonium nitrate, and ureas leave an acid residue. There is some disagreement as to the amount of the residue (Pierre, 1933; Andrews, 1954) with the latter suggesting larger residual effects. However the official A.O.A.C. method is based on the data by Pierre (Table XVI).

Hence applications of 100 lb. or more per acre of N over a period of years considerably accelerate lime needs.

The increased amounts of residues produced by higher rates of nitrogen result in greater production of such acids as carbonic, sulfuric, nitric, and certain organic acids when these residues decompose. These acids replace the bases from the exchange complex and speed leaching of cations.

TABLE XVI

Acidity with Synthetic Nitrogen Sources
(Pierre, 1933)

Source of nitrogen	Acidity per 20 lb. N in terms of pounds of $CaCO_3$
Ammonium sulfate	107
Monoammonium phosphate	100
Anhydrous ammonia	36
Ammonium nitrate	36
Urea	36
Sodium nitrate	36 (basic)

B. Phosphorus

Much note has been made of the fact that liming acid soils increases availability of native and applied phosphorus. Robertson *et al.* (1954a) found this to be true when liming low phosphorus soil up to pH 6.5 with soil high in sesquoxides. There was no effect when sesquoxides were low. Reduction occurred at a higher pH. Liming soils high in phosphorus reduced the availability of applied phosphorus presumably because of increased availability of native phosphorus. MacLean and Cook (1955) found greatest uptake of phosphorus by alfalfa at the highest lime level studied, pH 7.5. The authors point out that since more phosphorus was removed by the crop with increasing soil pH, it might be expected that the decline in native phosphorus as a result of cropping would become greater with liming.

Thorp and Hobbs (1956) noted that liming acid soils increased the yield of alfalfa and hence the availability as measured by total amount taken up. The percentage of phosphorus in the plant was below the critical point of 0.27 per cent and there were no significant effects on percentage. However, Lawton and Davis (1956) found that on an organic soil liming decreased rather drastically the phosphorus content of field beans, Sudan grass, and corn. One possibility is that lime increases the ratio of $HPO_4^{=}$: $H_2PO_4^{-}$ in the solution which in itself reduces phosphorus absorption (Hagen and Hopkins, 1955). Too, the great increase in biological activity brought about by liming may have immobilized the phosphorus in the microbial tissues.

It is of interest that on low phosphorus mineral soils in Wisconsin lim-

ing releases adequate quantities of phosphorus for alfalfa. Thus far on these soils lime and potassium are the main fertility requirements.

C. Potassium

There are many conflicting reports concerning the effect of liming on availability of potassium to plants. Southern soils and those from Hawaii have been found to release potassium with liming. Investigators have reported that soils from Iowa and Wisconsin released more potassium under acid conditions. Pratt *et al.* (1956) state that since acid soils are in reality Al-H soils the study of the effect of liming on K release by a procedure that makes an H-soil is not realistic. These researchers worked with Al-soils and with H-soils and in all instances the Al-soils give a lower release than H-soils both with and without liming. The release of potassium with various ions in the exchange complex for soils of Ohio was in the order $Ca > H > NH_4 > Al$.

An important point to consider in respect to liming acid soils for legume production is that as liming increases yields, larger quantities of potassium are removed from the soil.

D. Magnesium

Magnesium can be supplied in the soluble form as the sulfate. Dolomitic limestone is perhaps a more economical source for most crops and fully as efficient providing the soils need liming. Key (1957) reports that dolomitic limestone tended to be more effective than calcitic lime plus applications of magnesium sulfate on corn and soybeans.

Magnesium is receiving considerable attention because of low amounts in certain soils and subsequent effect of the high amounts of potassium on uptake of magnesium. McColloch *et al.* (1957) and Foy and Barber (1958) report that heavy rates of potassium increased magnesium deficiency symptoms on citrus and corn respectively. The latter investigators indicate that yield-limiting magnesium deficiency symptoms of corn are not likely to be produced by recommended amounts of calcitic lime and potash on the sandy soils of Indiana. In setting the stage for high yield levels however, in all probability such deficiency symptoms would be an indication that magnesium is limiting.

VII. Moisture and Fertility

More and more attention is being directed toward water needs of crops. The majority of our farmers rely on the rainfall during the crop season and the moisture stored in the soil. The level of fertility influences: (a) How

much water will be used from the soil. (b) How much crop will be produced from each inch of water.

Of course the increased yields produced with supplemental water result in correspondingly greater removal of plant food.

A. Root Penetration

1. *Corn*

Soil treatment affects extent of root growth and hence the depth of reservoir from which the plant can drain water. Fehrenbacher and Snider (1954) have studied the effect of plant nutrient level on root penetration (Fig. 23a, b). In a well fertilized rotation the roots of corn penetrated

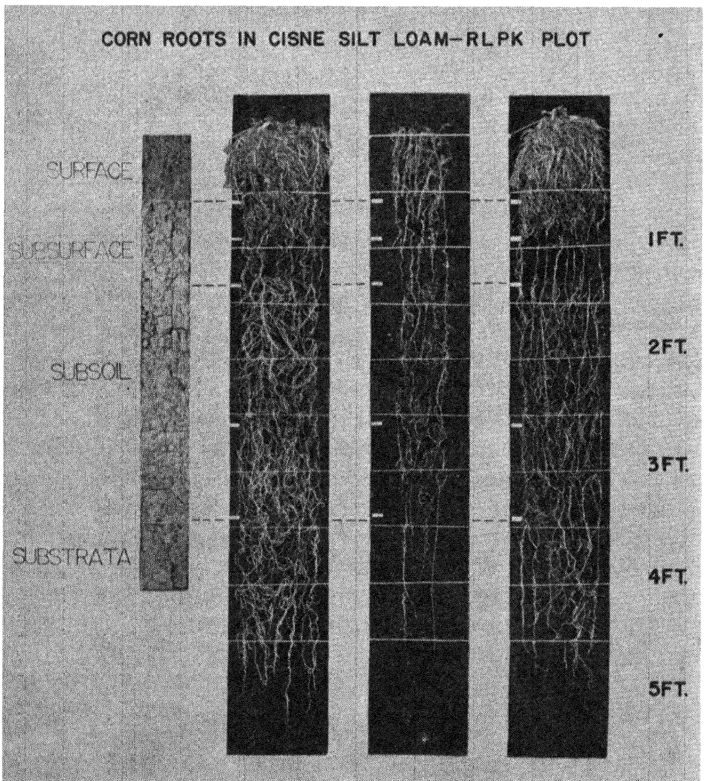


FIG. 23a. Well fertilized corn plants penetrate the soil to a greater depth. Hence they should be able to weather temporary droughts more successfully than inadequately fertilized plants. (Rotation includes corn, small grain, and legumes on Cisne silt loam, Toledo, Illinois) (Fehrenbacher and Snider, 1954).

considerably deeper than the corn in the check areas. Fehrenbacher and Rust (1956) likewise studied this same problem.

Studies at the Midwest Claypan Soil Conservation Experiment Farm at McCredie, Missouri, showed that on August 17, 1953 there was one inch of available water in the top 42 inches of soil under well fertilized corn (Fig. 24). Where no fertilizer was applied there was 4.5 inches. However on the well-fertilized plot the amount of water needed per bushel of corn was 5,600 gallons while on the low fertility area it was 21,000 gallons. Can we afford to be this wasteful of water?

2. *Legume Hay*

Pesek *et al.* (1955) report increased efficiency in use of water by legume hay when fertilized properly with phosphorus and potassium. *They emphasize however that in extreme drouth where the subsoil is dry or at least dry below two or three feet increased fertilization will not help crops to penetrate the soil further and get more moisture.*

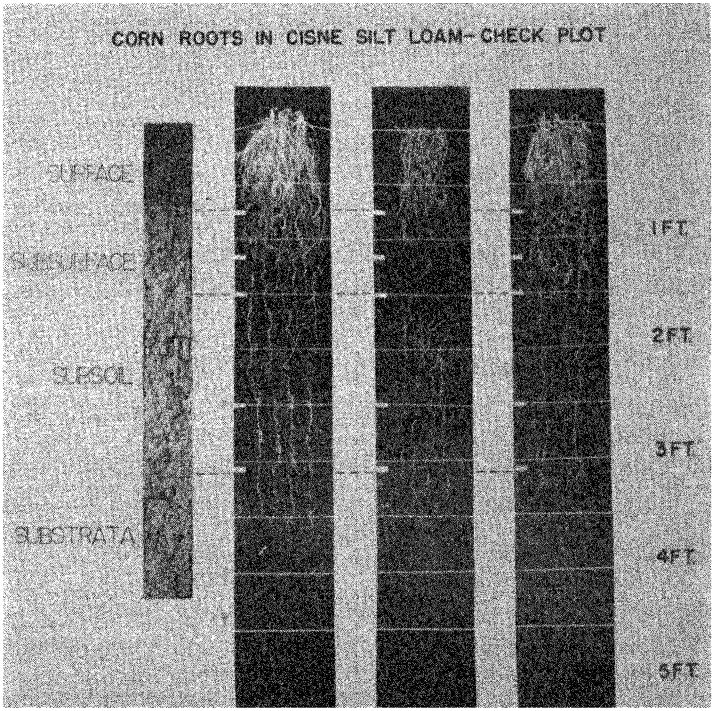


FIG. 23b. Soil penetration of inadequately fertilized corn plants.

3. *Small Grain*

Kmoch *et al.* (1957) observed that nitrogen fertilizer increased weights of wheat roots at nearly all soil depths. They state that the more extensive development permitted more complete utilization of subsoil moisture.

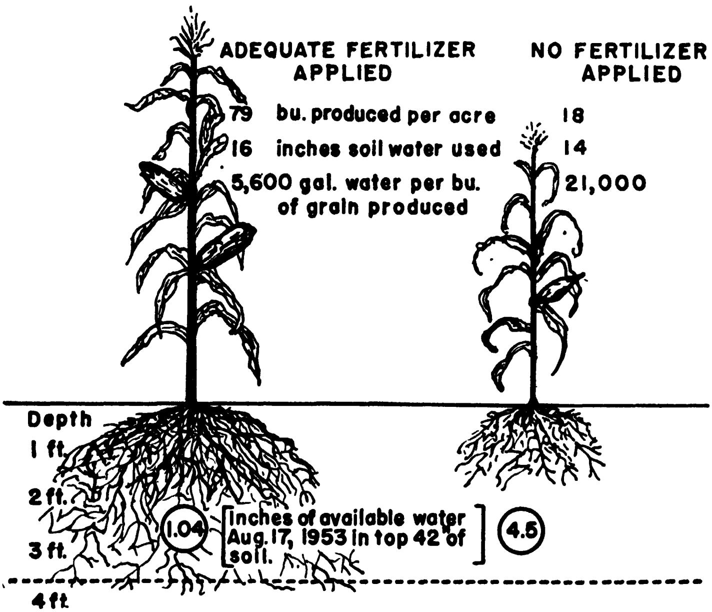


FIG. 24. Corn on soil with inadequate nutrients cannot develop sufficient root system to utilize subsoil moisture effectively (Smith, 1953).

4. *Water Holding Capacity and Depth of Rooting*

Soils vary in water holding capacity depending on texture, structure, and organic matter. For example Odell (1956) reports the water holding capacity in the surface 5 feet of representative soils as follows:

Oquawka sand	5 inches
Ridgeville fine sandy loam	7 inches
Swygert silt loam	9 inches
Muscatine silt loam	12 inches

The moisture holding capacity of many soils is satisfactory but plants may not use all available moisture. Fehrenbacher and Rust (1956) found that corn roots differently in various soils because of tightness of the soil or nutrient supply. For example Odell (1956) shows results as given in Table XVII.

TABLE XVII

Corn Roots and Available Water in Selected Soils (Odell, 1956)

Type of soil	Approximate depth of rooting (in feet)	Water available (in inches)
Clarence silt loam	3	6½
Saybrook silt loam	4½	10½
Muscatine silt loam	5+	14

McKenzie (1957) has estimated the available water in the surface 5 feet and in the corn root zone for the major series in five soil areas in Illinois.

The fertility level of the subsoil affects the responses to applied nutrients. Hanway (1956) has plotted the pH, phosphorus and potassium levels in representative soil types in Iowa. These data are used in conjunction with soil test information on the surface soil to develop fertilizer recommendations. How deep the roots go into the subsoil affects how much of the nutrient supply can be tapped. In a subsoil low in potassium more potassium could be obtained by the plant if it penetrated to 4 feet rather than 2 feet. Hence not only the fertility level of the subsoil must be known but also how deep the plant can effectively penetrate. This represents an area in which much further study is needed.

B. Fertility and Water Requirement

Kelley (1954) indicates that as far back as 1912 Nebraska workers showed manure greatly improved the effectiveness of water for corn (Table XVIII).

TABLE XVIII

Improved Effectiveness of Water for Corn with Use of Manure (Kelley, 1954)

Soil	Lb. of water per lb. of dry ears	
	No manure	Manure
Infertile	2136	692
Medium fertility	1160	679
Fertile	799	682

Kelley (1954) reports that under irrigated conditions on a low phosphorus soil, phosphorus decreased the amount of water required for each ton of hay (Table XIX).

TABLE XIX

The Effect of Phosphorus on Water Requirements of Hay (Kelley, 1954)

P_2O_5/A (lb)	Average yield (ton/A)	Inches of H_2O per ton of hay
100	8.2	11.7
200	9.1	9.5
400	10.7	8.2
600	11.1	7.7

Hanks and Tanner (1952) show that additional nitrogen increased the number of bushels of corn and oats produced per inch of water (Table XX).

TABLE XX

Effect of Increased Nitrogen on Corn and Oats Produced Per Inch of Water (Hanks and Tanner, 1952)

Crop	Bushels per inch of water	
	Low N	High N
Unirrigated		
Corn	2.7	3.6
Oats	1.8	4.0
Irrigated		
Corn	2.7	3.9
Oats	2.6	4.1

Hildreth (1956) reports that fertilizer (60–30–30) caused forage to use rainfall about twice as efficiently (Fig. 25).

There has been evidence presented showing that even though fertilizers increase yield there is little more water used. This is explained by the fact that losses by transpiration and evaporation in a heavy foliage crop are about the same as in a light foliage crop. Zubriski and Norum (1955) re-

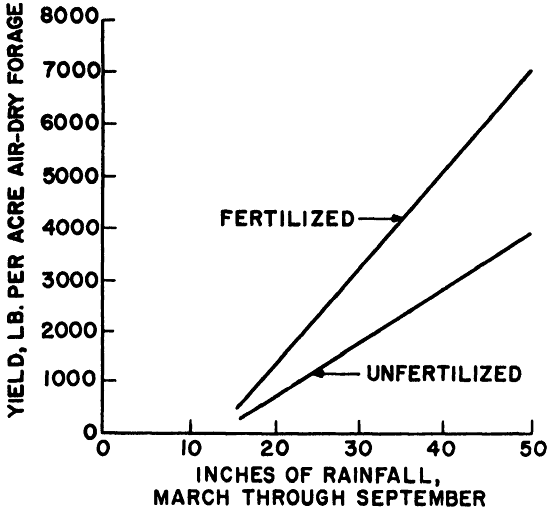


FIG. 25. Fertilizer (60–30–30) caused forage to use rainfall about twice as efficiently (Hildreth, 1956).

port that even though fertilizer greatly increased the yield of wheat, moisture content of the soil at harvest time was similar in fertilized and unfertilized plots as shown by an average of 12 trials (Table XXI).

TABLE XXI

Moisture Content of Fertilized and Unfertilized Soils After Wheat Harvest (Zubriski and Norum, 1955)

	Yield per acre (bushels)	Water in 5 feet of soil at harvest (inches)
Check	13.1	7.8 inches
Fertilized	17.9	7.8 inches

They state that while fertilizer is not a substitute for soil moisture well fertilized crops make more efficient use of the soil moisture available.

Extensive studies on the influence of soil properties on the rooting of alfalfa have been carried out for many years in Nebraska. Fox and Lipps (1955) report that calcium and phosphorus influenced the development of roots at lower depths.

C. Irrigation and Fertilizer Needs

Certainly the relationship of moisture and fertility is important in irrigated fields. If yields of 180 bushels rather than 90 bushels of corn or 6 tons rather than 3 tons of alfalfa are to be obtained, the nutrient removal is doubled. This means that the soil must supply more from some source, either from the native supply or from applied fertilizer. Parks (1955) emphasizes the need for more information on the effects of irrigation on efficiency of uptake of nutrients from the soil.

Agricultural leaders insist that before a grower invests in irrigation he try bringing all the production factors such as stand, nutrient supply and pest control up to top level. Most growers have these practices (less costly than irrigation) much below adequate levels.

VIII. Grower Demands

Many of the changes in fertilizer application which have taken place and will take place are directly related to that which the grower demands. His demands are influenced by costs, service furnished, and ease of handling. Because of changing technology it is always difficult to predict what economies will be effected in a chemical industry. When a product is first developed there are often dire predictions that it will not be practical or economical. However, through intensive research and study, industry develops and refines processes and procedures to bring new products into line competitively. The statement *"What is good for the farmer is good for the fertilizer industry"* has wide application.

A. The Farmer and His Pencil

One of the most useful tools to the farmer is his pencil. Its most profitable use to him is to figure probable returns from adequate quantities of nutrients. Another important role the pencil can play is figuring the most economical method of fertilization.

1. High Analysis Goods

Miller (1956) has suggested methods of comparison of high analysis fertilizers. In Kentucky county extension meetings, savings which might have been made if the farmers used the higher analysis goods are calculated. It was estimated that in 1956 Kentucky farmers could have saved one-half to one million dollars by purchasing higher analysis goods.

2. Materials

The cost per pound of nutrients and cost of application enter into the calculations. The variation in price of plant nutrients in materials is well

known, with nitrogen materials receiving the most attention because of the numerous new products which have been developed. In synthetic nitrogen production anhydrous ammonia is the product of the first step in the process. Basically then this is the cheapest material as such.

Cost of application is an important consideration with anhydrous ammonia, however, and must be added to the cost. The increasing popularity of anhydrous ammonia is a good example of calculation of costs and development of improved methods of application (Table XXII). In the fiscal year ending July 1, 1956 Adams (1957) reports that 30 per cent of the total direct application nitrogen was anhydrous ammonia—more than anv other single source.

TABLE XXII

Annual Consumption of Nitrogen as Anhydrous Ammonia (Adams, 1957)

Year[a]	Quantity (tons)	Portion of total direct application N (per cent)
1947	22,397	7
1948	35,556	10
1949	53,789	13
1950	70,123	14
1951	97,107	15
1952	137,983	18
1953	178,074	20
1954	287,155	26
1955	290,337	25
1956	343,550	30

[a] Years ended June 30.

3. *Mixed Fertilizer*

In many instances the grower is faced with the choice of using all mixed fertilizer, part mixed and part straight materials, or all straight materials. A knowledge of the method of calculation of costs is important.

For example a farmer has a choice of 12–12–12 or 6–12–12 plus a nitrogen material. Assuming 6–12–12 costs $56.00 and 12–12–12 costs $74.00 the extra 6 per cent nitrogen or 120 lb. costs $18.00 or 15 cents per pound. The cost of the supplementary nitrogen and any additional labor required in application must of course be considered.

Armstrong and Hull (1956) report that the actual cost of spreading commercial fertilizer broadcast was $1.30 an acre in Iowa. This compares

in general with charges for bulk solid or liquid fertilizer broadcast. The cost for anhydrous ammonia application will ordinarily be somewhat higher.

With row and small grain crops a certain amount of mixed fertilizer is essential as a starter under most conditions. The grower then has considerable freedom in choosing the method of application of the remainder of the nutrients.

B. Convenience and Service

One important factor which has helped to change concepts in fertilizer use has been the shortage of labor. It appears that the trend toward less and less labor will continue. In looking for ways to save labor the farmer can go to higher analysis goods, little storage on the farm, bulk spreading by the fertilizer industry, liquids, bulk fertilizer, etc. Sorenson and Hall (1956) indicate that bulk spreading may not result in direct cash savings but will eliminate a job the farmer performs himself. Ordinarily bulk fertilizer spread costs about the same as bagged fertilizer delivered to the farmer's storage. Bulk pickup of fertilizer by the farmer results in savings because of elimination of bags and certain handling costs. Storage is difficult however, and direct usage may be employed.

Service is a difficult factor to evaluate and just how much a farmer will pay for it is questionable. Service may include personal contact on needs such as taking soil samples for official or company tests and recommendations. Fully as important a service is the observation of the growing crops in the field, and with tissue tests the determination of what was done wrong.

Obviously service such as this costs money. It can exist with free competition only if the service increases volume of business to a level which will more than offset the expenditure in service.

C. Liquid Versus Solid

Many questions are being raised as to the future of liquid fertilizers. Tonnage is increasing and *future development will depend on comparative cost per pound of nutrients applied in the field and on actual conveniences.* Agronomically solids and liquids are equal. Gravity machinery for applying liquids to row crops is being developed. A problem for both the grower and the dealer is storage.

Slack (1957) states that the major problem in liquid mixes is the cost of raw materials. The geographic sections which have the least differential between the cost of superphosphate and phosphoric acid have the fastest rate of growth of liquid mix plants. The precipitation problem with wet-

process acid (a cheaper form) is being studied by a number of agencies. If this problem is overcome liquid fertilizer will be in a better competitive position.

In the United States the number of liquid plants, 72 in 1955, increased to 166 in 1957, with the greatest increases in Ohio, Indiana, Illinois, and Iowa.

Liquid mixes do not have the driving force of cost differential between liquid and solid forms that is the main advantage of anhydrous ammonia over solid forms of nitrogen. Technological advances in either industry can alter the economic advantage of either liquid or solid.

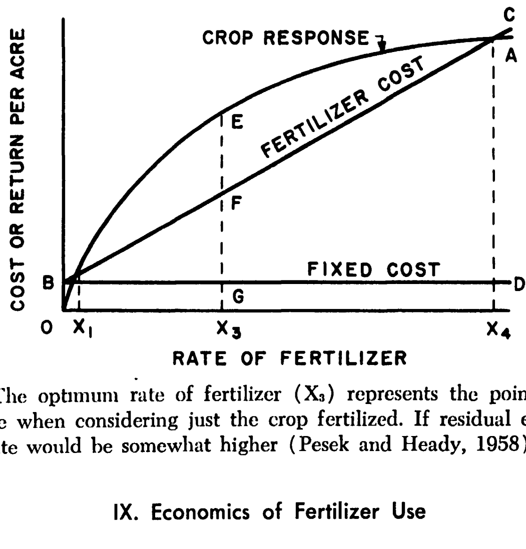


FIG. 26. The optimum rate of fertilizer (X_3) represents the point of maximum profit per acre when considering just the crop fertilized. If residual effects are considered the rate would be somewhat higher (Pesek and Heady, 1958).

IX. Economics of Fertilizer Use

Pesek and Heady (1958) have pointed out that in any situation the ideal quantity of fertilizer lies between an upper (optimum) and a lower limit (minimum). It is largely determined by the capital position of the farmer and probable returns that he may expect to realize from alternative uses of the same capital. The upper limit is defined as the "optimum" rate. In Fig. 26 this is X_3 units of fertilizer corresponding to a gross return, E, on production curve OA (Pesek and Heady, 1958). At point E, the tangent to the curve is parallel to the "fertilizer cost" line, BC. Beyond this point, an additional increment of fertilizer would cost more than the value of the extra crop yield produced. If no better alternatives for use of an adequate source of capital were available, it would usually be profitable to fertilize to this optimum level. Although EF represents maximum net return, it is

clear that total profit declines gradually in progressing to lower or higher rates from X_3.

The picture is not quite complete, however, for only the returns from the crop receiving fertilizer are considered. In section V 1 a, an instance is cited (Fig. 14) in which crop returns from residual nitrogen, for example, were sufficient to pay for the initial application. With this in mind the actual optimum rate would be higher than indicated by X_3.

In Fig. 27, also from Pesek and Heady (1958), the per cent profit (EF/EG of Fig. 26) is plotted against rate of fertilization. Until rate X_1

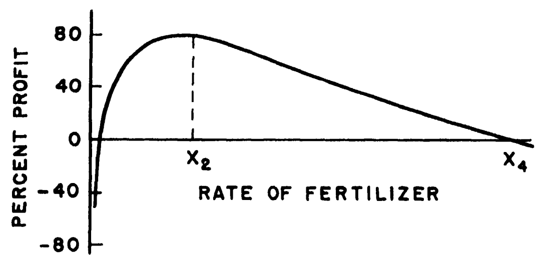


FIG. 27. X_2 represents the point of maximum return per dollar invested in fertilizer and defines the "minimum recommended rate." Fertilizer rates below X_2 result in a decrease in return on investment as well as profit per acre (Pesek and Heady, 1958).

(the minimum profitable rate) is reached, there is no profit from use of fertilizer. The average returns reach a maximum at X_2 which is designated as the "minimum recommended rate." Below rate X_2, both return on investment and profit per acre decrease. When less than the optimum rate (X_3, Fig. 26) is used, however, average return on the investment increases (i.e., efficiency increases) until X_2 level is reached. With very limited resources, it would be more profitable to fertilize a certain minimum acreage at the X_2 rate, leaving the remaining acres unfertilized, than to fertilize the entire acreage at a rate less than X_2. It should be kept in mind that under normal economic conditions and good management, bankers stand ready to loan money for fertilization to X_3 in order to allow the greatest profits per acre.

Hanway and Dumenil (1955) developed a relation between nitrogen soil test and yield increase of corn from applied nitrogen for first-year corn in Iowa. They then estimated optimum rates of nitrogen as a function of prices and nitrogen soil test. With application of two or more nutrients at various rates and combinations, economic analysis becomes more complex, particularly when residual effects also are taken into account.

In this country, several large-scale studies are underway in which econ-

omists and agronomists are attempting to arrive at suitable experimental designs and analytical methods for determining crop response surfaces. Procedures and objectives of these investigations have been discussed by several authors in two recent volumes edited by Baum *et al.* (1956, 1957).

X. In the Future

A. Potential Nutrient Needs

Usage of nitrogen, phosphorus, potassium, and lime is much below optimum in most areas. Official agricultural leaders often are heard to state that plant nutrient usage could be more than doubled. Bennett (1956) stated that, based on a summary of soil tests in Iowa, present usage of potassium could be increased ten times, and phosphorus and nitrogen four times.

It is of course difficult to reach potentials, and as usage begins to approach the goal, new goals are set. Continual improvement of germ plasm, pest control, and moisture control help to raise crop yield potentials and hence plant nutrient needs.

B. Research Needed

Adoption of research findings by farmers on a widespread scale results from systematic coordination of the objectives and educational activities of all agencies involved. Similarly, recognition that greatest progress in research is not achieved through independent action has led to establishment of various research organizations and committees to facilitate conduct of research on problems of regional and national significance. Tangible evidence of achievement through such an approach is seen in the work of the regional and national soil test work groups, the phosphorus, nitrogen, and potassium work groups, and others.

Continued emphasis is needed in the following general areas of research:

1. Quantitative definition of soil characteristics which govern fertilizer behavior and effectiveness of applied nutrients.

2. Fertilizer characteristics (chemical and physical) which make for most efficient use of applied nutrients in relation to specified soil properties.

3. Fertilizer use practices such as placement, time of application, and rate of application in relation to (1) and (2).

4. Fertilizer use by different crops and variety of a given crop in relation to (1), (2), and (3) and in relation to moisture and other climatic variables.

Soil testing is an important connecting link between soils research and fertilizer usage. It appears obvious that further progress and refinement in soil testing or other practical diagnostic techniques and their translation into sound recommendations hinges particularly upon well oriented research within the above framework. Increased emphasis must be given to fundamental studies. Evidence of substantial recent progress in these areas has been cited briefly in the foregoing pages. There is, however, danger of becoming overly complacent regarding the present status of our fundamental knowledge of soil and fertilizer characteristics. Improvements here most certainly will continue to provide more accurate answers to the many questions raised relative to factors influencing efficient use of fertilizers.

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RACE 15B OF WHEAT STEM RUST—WHAT IT IS AND WHAT IT MEANS

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I. Why Race 15B Is Notorious

Race 15B of wheat stem rust, *Puccinia graminis* var. *tritici*, has become notorious to every one interested in wheat improvement in North America.

[1] Many of the data and conclusions in this paper are the result of cooperative investigations between the U.S. Department of Agriculture and the Minnesota Agricultural Experiment Station. Paper 3864, Sci. J. Series, Minnesota Agr. Expt. Sta.

In 1950 this race suddenly and without warning extended its geographical range over most of North America, increased abruptly and alarmingly in prevalence, attacked previously resistant bread wheats and durums, proved to be complex in composition, and has continued to be one of the principal obstacles to the production of resistant varieties of wheat since that time. That race 15B finally became widely established is not surprising in itself, but it is surprising that it increased and spread so suddenly and spectacularly in a single season, after it had been watched carefully during the previous decade without showing any tendency to increase in prevalence or to extend geographically.

II. The History of Race 15

Race 15B was first definitely recognized in the United States in 1939, when it was isolated from barberries near Fort Dodge, Iowa (Stakman and Loegering, 1951).[2] But race 15, from which 15B is not clearly distinguishable on the 12 standard differential varieties of wheat, has been known since 1918. Although race 15 was never prevalent enough to be economically important in the United States, it was rather widely distributed in several years, principally in association with barberry bushes. As examples, it was isolated from barberry in Minnesota, Wisconsin, Iowa, Indiana, and West Virginia in 1936, and in North Dakota, South Dakota, Iowa, Kansas, Wisconsin, Michigan, Ohio, and Pennsylvania in 1940. There was circumstantial evidence that the wind had carried spores considerable distances from barberry bushes in some seasons, but there is very strong evidence that race 15 survived from season to season in the telial stage only, and was therefore dependent on the barberry for its persistence.

In 1918 and 1919 race 15 was isolated 2 times and 5 times, respectively, from uredial material, but it was not found again in the United States until 1929 when one isolate was obtained among the 720 isolates identified. From 1930 to 1942, inclusive, race 15 was found in uredial collections each year except in 1932, 1934, 1935, and 1941, but its highest prevalence was only 0.6 per cent of all isolates identified. It is noteworthy that it was not present among the 1493 wheat rust isolates identified in the epidemic year of 1935. From 1944 to 1948, inclusive, race 15 was not found at all in uredial isolates, but it has been isolated each year from 1949 through 1956, always with a percentage prevalence of less than 1 per cent of racial isolates, except in 1956 when it was 1.1 per cent, the highest since 1919. Of about 25,000 isolates identified from collections of uredial mate-

[2] Data regarding *Puccinia graminis* for which specific references are not given are either personal observations on the part of the writers or are taken from records in the Cooperative Rust Laboratory at St. Paul, Minnesota.

rial in the United States during the past 40 years, only 76 were of race 15. Of these 19 were prior to 1939 when 15B was first distinguished and 42 were found in the 32 years from 1918 to 1949, inclusive. Some of these uredial isolates were obtained near known barberry bushes and others in barberry infested areas, with strong circumstantial evidence that the initial inoculum had come from the bushes. Aecial isolates, 1918–1949, inclusive, totaled 59, of which 21 were obtained prior to 1939 and 38 subsequently.

III. The Early History of 15B

There is circumstantial evidence that 15B may have been present in the United States before 1939, as some isolates of race 15 appeared to be more virulent than others. Unfortunately, the early attempts to devise methods for distinguishing clearly between these isolates were not successful. An isolate in Japan, however, was so distinctly less virulent than most of the North America isolates of race 15 that it was designated as 15A (Loegering and Stakman, 1942). For this and other reasons the search for additional differentials was intensified. In 1939 it was found that RIVAL wheat was more susceptible to some isolates than to others. Those to which it was only moderately susceptible continued to be designated as race 15, and those to which it was more susceptible as 15B. RIVAL, however, was not completely reliable as a differential. An Australian hybrid, KENYA × GULAR, was more satisfactory than RIVAL, but it was not possible to replenish the supply of seed during World War II, and, since no completely reliable differential was available, a number of isolates that were almost certainly 15B were included in the record as race 15. Finally the variety LEE, released in 1951, was tested, and, when purified seed was obtained, proved satisfactory for separating isolates of race 15 into two groups: Those to which it was resistant were designated as 15, and those to which it was susceptible as 15B.

Three important facts should be emphasized. First, it seems probable that among the isolates designated as race 15 between 1918 and 1939 some might have been designated as 15B had satisfactory differentials been known during that period. The second important fact is that the search for good differentials to distinguish clearly between the various biotypes within 15 was unsuccessful until new varieties of wheat, especially LEE, became available. The ability to distinguish clearly between biotypes or groups of biotypes within races is therefore sometimes dependent on the development of new biological indicators—new selections and varieties of wheat. Third, it was not until 1950 that race 15B became prevalent enough to furnish a really good sample of isolates for thorough study. Since that time it has been distinguished consistently as a sub-race.

IV. The Prevalence of Race 15 and 15B, 1918–1949

The prevalence of race 15, including what is known about 15B, through 1949 is given in Table I.

It is evident from Table I that race 15 made threatening gestures in 1940, when 18 uredial and 12 aecial isolates were obtained from a rather wide area. But in 1941 it was not found at all in uredial collections although isolated 9 times from aecial material from 5 states. From 1941 to 1949, inclusive, only 3 uredial isolates and 23 aecial isolates could be found. Although race 15, and especially 15B, was long a cause for concern, it was not a cause for alarm until 1950.

V. The Explosive Spread and Establishment of Race 15B in 1950–1951

In 1950 race 15B was distributed from Texas to Manitoba, and from Wyoming, Idaho, and Colorado on the west to Michigan on the east. It appeared in rust collections from 16 states: Colorado, Idaho, Illinois, Iowa, Kansas, Michigan, Minnesota, Missouri, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, Wisconsin, and Wyoming. It comprised 27 per cent of the 1180 isolates identified in the United States during the growing season of 1950.

Even after 15B astounded everyone because of its sudden increase in prevalence and extension of distribution in 1950, there still was hope that it might not become permanently established independently of barberry. But events decreed otherwise. Harvest in the spring wheat area of the United States and much of Canada was extremely late in 1950. Some wheat matured at least five weeks later than in a normal year, and some of it never ripened at all, thus giving the initially relatively small amount of 15B several weeks longer to multiply than in a normal season. Moreover, weather conditions were favorable for abundant rust development on late wheat and on the wild *Hordeum jubatum*. Heavy rust development on grasses during late summer and early fall in northern United States is not unusual, although in 1950 the rust had the additional advantage of being able to multiply on the late wheat also. In most years relatively dry weather and killing frosts in northern United States tend to eliminate the uredial stage fairly early in the fall. Unfortunately, however, rains continued in many areas through the fall of 1950, and the first killing frosts were much later than usual. In the meantime, air mass movements carried clouds of spores southward to infect fall-sown wheat in southern United States, in central Mexico, and even in the wheat growing areas of northwestern Mexico. The uredial stage of the rust then persisted during the winter in Mexico, and possibly in extreme southern United States, and spores were again blown northward in the spring of 1951.

TABLE I

Number and Location of Uredial and Aecial Isolates of Race 15 of Wheat Stem Rust, 1918–1949

	Uredial isolates[a]		Aecial isolates[a]	
Year	Number	Location	Number	Location
1918	2	South Dakota, Tennessee	0	·
1919	5	Minnesota, Mississippi, Missouri, Montana, South Dakota	0	—
1920–1928	0	—	0	–
1929	1	Kansas	2	Maryland, Wisconsin
1930	1	Nebraska	0	—
1931	3	Minnesota 3	0	–
1932	0	—	0	–
1933	1	Minnesota	0	—
1934	0	—	1	Wisconsin
1935	0	—	0	—
1936	1	Wyoming	8	Indiana, Iowa 3, Minnesota 2, West Virginia, Wisconsin
1937	2	Texas 2	2	Iowa 2
1938	3	Iowa, Kansas, Texas	8	Indiana, Ohio 2, Pennsylvania 2, West Virginia 3
1939	3	Indiana, South Dakota, Wisconsin	3	Missouri, Pennsylvania, *15B in Iowa*
1940	18	Michigan, Minnesota 2, Missouri 4, Nebraska, Ohio, Oklahoma 3, South Dakota, Texas 4, Wisconsin	12	Iowa 2, Kansas, Michigan, North Dakota, Ohio, Pennsylvania 4, South Dakota, Wisconsin
1941	0	—	9	Michigan, Minnesota 2, Virginia, West Virginia 2, Wisconsin 3
1942	1	Minnesota	3	Colorado, West Virginia 2
1943	1	Wisconsin	0	—
1944	0	—	1	Maine
1945	0	—	0	—
1946	0	—	1	Virginia
1947	0	—	2	Nebraska 2
1948	0	—	5	Illinois, Ohio, *15B in Michigan, Pennsylvania, Virginia*
1949	1	Idaho	2	Pennsylvania, *15B in Virginia*

[a] One isolate from each State unless otherwise indicated. All isolates are designated as "uredial" if obtained from uredial material, even though collected in the immediate vicinity of barberry bushes (Stakman and Loegering, 1951).

An unusual series of events in 1950–1951, therefore, not only enabled race 15B to become widespread during the growing season of 1950 but also to become widely and permanently established in Mexico where it can survive throughout the year in the uredial stage, and thus persist independently of barberry, on which it clearly had been dependent prior to 1950. Naturally, the telial stage is now far more prevalent and widely distributed than formerly in northern United States, consequently the chances of abundant development of the aecial stage on barberries are greatly increased also. The rust therefore now has double life insurance: (1) the uredial stage, which can persist in Mexico and occasionally in southern United States; (2) the telial stage, which can cause infection on the barberries that still remain in northern United States. Obviously, the opportunity for genetic variation in 15B is now increased also because the telial stage is more abundant and widespread than formerly in northern United States and the chances for the development of numerous aecial infections over a wide geographic area are greatly increased.

VI. The Percentage Prevalence of 15B in the United States, 1950–1956

Race 15B evidently is here to stay, even though its percentage prevalence has decreased somewhat from the high of 63 per cent in 1953, as shown in Table II (Stakman and Loegering, 1951; Stakman and Stewart, 1953, 1954; Stakman *et al.*, 1955; Stewart *et al.*, 1956, 1957).

TABLE II

The Prevalence of Race 15B of Wheat Stem Rust in the United States by Years, 1950–1956, Based on Number of Uredial Isolates and the Percentage of Total Isolates

Year	Total isolates	Number of 15B isolates	Percentage of total	Relative rank
1950	1180	317	27	2
1951	950	383	40	1
1952	1279	746	58	1
1953	1025	648	63	1
1954	1481	713	48	1
1955	755	356	47	1
1956	1005	302	30	2

VII. The Scientific and Practical Importance of 15B

The same factors that enabled 15B to spread so far and so fast in 1950 also enabled certain other races of wheat stem rust to spread fast and far, as indicated by the unusual occurrence of races 11, 32, 34, 40, 48, 52, 69,

142, 186, and an entirely new race. None of these races has had quite so spectacular a career, however, as 15B. Race 7 of oats stem rust, however, rivals the record of 15B and will therefore be discussed later.

Scientifically, race 15B is interesting because it illustrates how suddenly the improbable can happen. From a practical standpoint, it is tremendously important because it completely upset the status quo with respect to varietal resistance in spring bread wheats and durums in the United States and Canada. All of the commercial bread wheats and the rust-resistant durums that seemed to have solved the stem rust problem have been either damaged severely or almost completely ruined by 15B at certain times and in certain places, when it had seemed that they might be permanently resistant. And it had taken a long time to produce them, as shown in the brief account which follows.

VIII. Vicissitudes in Breeding Rust Resistant Wheats in the Past

Systematic breeding for stem rust resistance in the United States was begun by the U.S. Department of Agriculture in cooperation with the Minnesota Agricultural Experiment Station shortly after the very destructive rust epidemic of 1904. Without tracing the details of the successes, frustrations, and failures, it had appeared several times that certain varieties might be generally and permanently resistant to all races of stem rust. Nevertheless, each variety had succumbed in turn to new races. It appeared that CERES, produced in North Dakota from a MARQUIS × KOTA cross, and released in 1926, might have solved the rust problem in spring wheat. However, race 56, first found on barberries in Iowa and Nebraska in 1928, two years after CERES was first released, increased slowly in prevalence for several years, then increased abruptly in 1934, a non-rust year, and ruined CERES in the terrific epidemic of 1935.

On the supposition that CERES might sometime rust, breeders in Canada and at several places in the United States had produced a number of varieties that owed most of their stem rust resistance to HOPE and H-44, both derived from a wide cross, MARQUIS × Yaroslav emmer, made by McFadden (1930) in South Dakota and released in 1926. So resistant had HOPE been in the field, where it was grown occasionally although not a good commercial wheat, that certain seedsmen offered a dollar for every rust pustule that could be found on it. The HOPE type of resistance was considered by many to be permanent and indestructible. Varieties had been developed that combined several other types of resistance also with that derived from HOPE or H-44. But none of them protected completely against race 15B.

Because much is now heard about broadening the genetic base for re-

sistance, it seems worth while to consider the early attempts to establish as broad a base as possible, in the light of information then available, even though subsequent events proved that the base was not broad enough. In the early breeding work carried on cooperatively by the U.S. Department of Agriculture and the Minnesota Agricultural Experiment Station, beginning shortly after the epidemic of 1904, attempts were made to combine the good qualities of the bread wheats with the rust resistance that appeared in certain of the other species groups, such as the einkorns, emmers, durums, and poulard wheats. Sterility and undesirable linkages were encountered so commonly that the view developed that there was complete linkage between the rust resistance and other undesirable characters of the emmers, durums, and other representatives of the species groups other than *Triticum vulgare*. Nevertheless crosses were made between MARQUIS, then the best bread wheat, and IUMILLO durum, as the latter seemed to have generalized field resistance even though seedlings were susceptible in the greenhouse to some collections of rust. Of more than 2,000 lines of a MARQUIS × IUMILLO cross, however, three appeared that combined the resistance of the IUMILLO with many of the desirable characters of the MARQUIS. One of these lines eventually became the variety MARQUILLO.

In the meantime the apparently immune hard red winter wheat KANRED had been selected at the Kansas station and released shortly after the epidemic of 1916. With the discovery of physiologic races within what was then commonly known as the biologic form *Puccinia graminis tritici*, however, it became apparent that KANRED was completely susceptible to some races even though it was immune from others. Crosses were therefore made between MARQUIS, which was itself resistant to some races, and KANRED, which was immune from certain others. Several varieties with the KANRED type of immunity from some races were produced, but they were not completely satisfactory because their reaction to rust in the field depended upon the presence or absence of certain rust races. It did appear, however, that a combination of resistance to a number of individual races, combined with the generalized resistance of IUMILLO durum, might protect against most races of rust that then prevailed in North America.

A double cross (MARQUIS × IUMILLO) × (MARQUIS × KANRED) finally resulted in the production of THATCHER, in a sense the most scientifically-produced wheat of its day (Hayes *et al.*, 1936). This is said without disparaging the scientific basis in the production of other varieties. THATCHER had been tested thoroughly against individual races and in nurseries in which epidemics had been created by inoculating artificially with all races of stem rust which were known to occur in North America. Although it

rusted very occasionally, it appeared that THATCHER was unlikely to rust when grown in the field away from the extremely susceptible varieties with which it was purposely associated in the rust nursery. THATCHER was therefore released in 1934 and made a spectacular debut in the epidemic of 1935, which destroyed approximately 100 million bushels of spring wheat in the United States, and in which CERES (MARQUIS × KOTA) was badly injured for the first time in its history. THATCHER, on the other hand, came through the epidemic unscathed and was ready to fill the breach that was left by the collapse of CERES.

It had been known that THATCHER was susceptible to orange leaf rust and to scab, but it was not realized how severely it could be damaged by these diseases in the moister regions where the spring wheat area and the corn belt overlap. This resulted in two developments: (1) THATCHER was pushed northward and westward, and (2) it was crossed with HOPE wheat, with the objective of incorporating resistance to leaf rust and scab and still more resistance to stem rust. This resulted in the production of NEWTHATCH.

NEWTHATCH probably had the broadest genetic base for resistance of any of the very excellent varieties that were replacing CERES. It resulted from the following crosses: [(MARQUIS × IUMILLO) × (MARQUIS × KANRED) × (MARQUIS × Yaroslav emmer)] × THATCHER^2 (Ausemus *et al.*, 1944). Simply stated, THATCHER × HOPE derivatives were backcrossed twice to THATCHER. NEWTHATCH, then, had physiologic resistance to certain rust races which it derived from MARQUIS, immunity from a number of races which it derived from KANRED, plus what seemed to be mature plant resistance, better designated perhaps as adult plant resistance, which it derived from the IUMILLO durum and the Yaroslav emmer. Like THATCHER, NEWTHATCH had been thoroughly tested in artificially induced epidemics created by inoculating with all races that were known to be prevalent in North America. It looked as if it would last for a long time.

IX. The Stem-Rust-Free Era in Spring Wheat, 1938–1949

During the period from 1938 to 1949, inclusive, stem rust was not an important factor in the spring wheat region of United States and Canada. In addition to THATCHER and NEWTHATCH, several other varieties, produced principally in Canada and North Dakota, and by the U.S. Department of Agriculture, also were generally resistant in the field. Virtually all of them derived most of their resistance from HOPE or H-44, a sister selection. Among the varieties that were highly resistant to stem rust in the spring wheat area were RIVAL, REGENT, RENOWN, MIDA, PILOT, THATCHER,

and NEWTHATCH. During the decade 1940–1950 several resistant varieties also were developed in cooperative work between the Mexican Ministry of Agriculture and The Rockefeller Foundation (Borlaug, 1954).

In the meantime the rust-resistant durum varieties STEWART and CARLETON had been produced in North Dakota by crossing the high-quality MINDUM with VERNAL emmer and then backcrossing twice to MINDUM (Smith, 1943). They were distributed in 1943, and it was very difficult to find any stem rust or leaf rust on them in the United States and Canada until 1950, although they were sometimes attacked by leaf rust races which prevailed in Mexico.

This was the situation, then, that prevailed from approximately 1938 through 1949 for the bread wheats and from 1943 through 1949 for the durums. All of the varieties previously mentioned and certain others were so resistant in the field that stem rust was not a factor in the production of spring wheat, even though conditions were favorable for the development of epidemics on susceptible varieties in several years during that period. Nevertheless the varieties that performed so well were exposed to infection by only four rust races in the field: 17, 19, 38, and 56. During the entire period these four races constituted 90 per cent or more of all of the rust isolates identified in the United States (Stakman and Loegering, 1941, 1942, 1943, 1945, 1948, 1950; Stakman *et al.*, 1942). The conclusion seemed justified therefore that barberry eradication and intelligent breeding for resistance had not only reduced the number of rust races but had also solved the stem rust problem in spring wheat for an indefinite period of time.

X. The Virulence of 15B for Previously Resistant Varieties

Then came the bombshell in 1950, when it became evident that race 15B might nullify the breeding efforts of more than three decades. Race 15B virtually identified itself in 1950, because none of the other prevalent races attacked the varieties commonly grown in the spring wheat area; accordingly large pustules which appeared on the previously resistant varieties proved so consistently to be 15B that the regular method of identification by the reaction of the differential varieties of wheat in the greenhouse would not have been necessary to determine the percentage prevalence of 15B. In retrospect this is strictly true, but there obviously was the possibility, before the event, that some of the large pustules might have been produced by races previously unknown in North America. The prognosis that the rust on the resistant varieties was caused by 15B proved to

be correct; at the time, however, it was highly probable but not certain. The events of 1950, and certain other years, show clearly the value of strategically distributed rust nurseries in reconnoitering for new or dangerous physiologic races. For it was in nurseries far south of the spring wheat region where 15B first signaled its upsurge in 1950.

It became clearly evident in 1950 that the resistant durums might be badly injured; some late fields were ruined, and the percentage losses in North Dakota and Minnesota were 22 and 35, respectively. Late fields of durum were severely injured in 1951 and 1952 also. In the latter year, a widespread epidemic was averted by providential weather, but the epidemics in durums in 1953 and 1954 confirmed the evidence that the previously resistant durums had no protection against 15B. There was reluctance for a time to believe that the resistant bread wheats could succumb completely to 15B, but subsequent events proved that they can. The losses in bread wheats and durums in the Dakotas and Minnesota since the advent of 15B are given in Table III.

TABLE III

Percentage Loss Due to Stem Rust in Durum and Bread Wheat in Minnesota, South Dakota, and North Dakota, by Years, 1950–1956[a]

	Loss in per cent						
Crop and State	1950	1951	1952	1953	1954	1955	1956
Durum wheat							
Minnesota	35	Trace	15	75	80	15	Trace
South Dakota	2	Trace	20	80	75	10	Trace
North Dakota	22	Trace	15	65	80	20	2
Bread wheat							
Minnesota	Trace	Trace	2	10	15	2	Trace
South Dakota	1	Trace	5	35	20	6	Trace
North Dakota	2	Trace	3	30	35	6	Trace

[a] Cooperative Rust Laboratory, St. Paul, Minnesota.

From Table III it is evident that race 15B destroyed about 75 per cent of the durum crop in the Dakotas and Minnesota in 1953 and 1954 and about 25 per cent of the bread wheat. This indicates clearly that the durums were more vulnerable than the bread wheats. The situation has been summarized as follows (Stakman, 1955): "Race 15B almost annihilated the durum crops in 1953 and 1954, and what durum there was in 1954 was very light and shrunken. The bread wheats of 1904 would have

suffered the same fate as the durums of 1954. The bread wheats of today can also be destroyed, but not so easily as those of 50 years ago. It takes more rust, more time, and more favorable rust weather to destroy them. There has been a net gain even though it is not enough to insure against destruction when weather and other factors favour early and intense epidemics."

Apparently the durums STEWART and CARLETON have only specific physiologic resistance to many rust races but none whatever to 15B. Some of the bread wheats, on the other hand, have certain morphologic characters that confer some degree of generalized resistance in addition to their specific resistance to many physiologic races, according to investigations made at the University of Minnesota under the supervision of Helen Hart. All characters that contribute to this generalized resistance deserve thorough study.

XI. Problems in Breeding for Resistance to 15B

The stem rust situation in Mexico, where spring wheat types are grown, and in the spring wheat area of the United States and Canada, was changed radically by the advent of race 15B. The change, however, had been anticipated as much as possible. As it was known that race 15B was appearing continually, although sporadically, near barberries in the United States and occasionally elsewhere, attempts were made to develop varieties that would resist its attack. Naturally, these attempts were handicapped because 15B was scarce and there was reluctance to create artificial epidemics which might encourage the establishment and spread of this potentially dangerous race. Nevertheless, crosses were made between good bread wheats and several other varieties, especially the most resistant known selections of the Kenya group. Several facts, however, became evident shortly after it became possible to test these and certain other varieties and hybrids against a larger sample of 15B than had been available prior to 1950: (1) It was found that certain Kenyas and their derivatives were highly resistant at temperatures up to approximately 80° F but completely susceptible at temperatures of about 85°; (2) It soon became evident that what had been designated as race 15B was a confederation of many biotypes, some of which probably were not in existence prior to 1950; or if they had come into existence near barberries, they certainly had not persisted. The concept of the taxonomic status of 15B therefore had to be changed.

As soon as several hundred collections became available for study, instead of the very small number that had previously been available, there

were two indications that isolates of 15B differed in pathogenicity. First, there were quantitative differences on some of the 12 standard differentials and LEE. Second, qualitative differences appeared on KHAPLI emmer: an isolate from Iowa produced the usual type-1 infection; one obtained from barberry in Virginia produced type 2; and one from Oklahoma produced an infection type that sometimes approached $3^{=}$. These observations made it possible to organize attempts to distinguish more clearly the biotypes within 15B. Before additional differentials were found, a number of isolates were tested side by side, and a quantitative determination of relative virulence was made by summing the infection types produced on the standard differentials. A sample of the data is given in Table IV. The values obtained made it seem probable, but not certain, that the isolates were different.

TABLE IV

Relative Pathogenicity of Two Isolates of Race 15B of Wheat Stem Rust on Standard Differentials and LEE Wheat at 70–75° F.[a]

Wheat variety	Infection type of isolates	
	F[b]	N[c]
LITTLE CLUB	4++	4+
MARQUIS	4+	4
RELIANCE	4+	4
KOTA	4++	4
ARNAUTKA	4++	4+
MINDUM	4++	4++
SPELMAR	4++	4+
KUBANKA	4++	4++
ACME	4++	4++
EINKORN	4+	4±
VERNAL	4+	4
KHAPLI	0; to 1−	1=
LEE	4+	4−

[a] Four other isolates differed similarly but in lesser degree.
[b] Numerical rating: F = 52.5.
[c] Numerical rating: N = 49.8.

When comparative studies were made of the isolates that produced the different infection types on KHAPLI, it was clear that there were distinct differences, as indicated in Table V.

It is evident from Table V that differences which appeared only interesting on KHAPLI were important on KENTANA 52. Nevertheless, isolates

TABLE V

The Infection Types Produced by Three Isolates of Race 15B of Wheat Stem Rust on KHAPLI emmer and KENTANA 52 Wheat[a]

Isolate	Variety and infection type	
	KHAPLI	KENTANA 52
Iowa	0 (almost immune)	1 (highly resistant)
Virginia	2 (very resistant)	3 (moderately susceptible)[b]
Oklahoma	1 to 3 (moderately resistant)	4 (very susceptible)

[a] Experiments made by Oscar Neri Sosa, of Guatemala, while a student at the University of Minnesota.

[b] The reaction is intermediate and could be considered either as moderately susceptible or moderately resistant.

similar to those from Virginia and Oklahoma were extremely rare in the field and were not encountered again for some time after they were first collected, although the same biotypes or similar ones were subsequently found. In the meantime, however, a large number of varieties of wheat and a considerable number of barleys were tested against a selected sample of isolates, and the results showed conclusively that there were decided differences among them.

Seventeen isolates that appeared to be somewhat different on the regular differentials, such as F and N in Table IV, were tested on 99 varieties of wheat and 17 varieties of barley, and 14 of them proved to be distinctly different on one or more of the 116 varieties.[3] The conclusion, therefore, is justified that race 15B comprises many biotypes, and the problem is to group them in a meaningful and useful way into sub-races, as it appears that it would be impossible to develop a taxonomic system that would distinguish clearly between all biotypes.

Attempts to classify the changing population of biotypes of 15B are still continuing. All that can be said with assurance from the practical standpoint is that there are extremely important differences between them, but exactly what these differences are and how important they are can be determined only by much more research. During the race survey of 1957 a considerable number of isolates from the United States attacked GOLDEN BALL durum heavily and others did not. In Canada, some isolates have been found to attack SELKIRK while others do not, but such isolates have been rare among those identified in the race survey of the United States in 1957.

[3] Tests made by Rosendo Postigo and Dr. Helen Hart.

XII. Increased Complexity in Physiologic Races of Wheat Stem Rust since 1950

Race 15B is not the only new problem. Certain hybrids in which KENYA was one of the parents and which seemed to be resistant to 15B became heavily infected in Northern Mexico and elsewhere by race 139, which had been found in nature in the United States for the first time in 1934,[4] but had never become prevalent. It had been found, however, in very small quantities in Northern Mexico for several years and provoked curiosity as to why it and race 49 were persisting there. As race 139 was always considered weakly virulent, it was surprising that it was so virulent on certain varieties which were resistant to 15B, certainly the most generally virulent race that had been known in North America up to that time. The effects of 139 have been counteracted in Mexico by certain other varieties, but in the meantime it became apparent that certain other groups of races had increased. Those that appear to be most important at present are the race 11–32 complex, the 17–29 complex, and the 38–48 complex. Race 11 had long been known and had been fairly prevalent in the early 1930's but decreased in prevalence, was not found at all from 1944 to 1948, inclusive, and appeared in small quantities only subsequent to that time. It is known now that there are biotypes of race 11, at least one of which produces a rather high infection type on KHAPLI emmer. Race 29 also increased. It had been known for some time but had never been widely prevalent, although the closely related race 17 was very common. There apparently was a shift from race 17 toward race 29, however, starting about 1950.

Race 15B and the other prevalent races have been held fairly well in check during the past three years, which, however, have not been epidemic years. It is known that SELKIRK, now the leading variety in the spring wheat region, is highly susceptible under some conditions as it has been heavily rusted in Puerto Rico and elsewhere. Moreover, the new durums, TOWNER, RAMSEY, LANGDON, YUMA, also are susceptible to certain isolates of the race complex that now exists. Attempts therefore must be continued to find as nearly universal resistance as possible. This is being done by testing in the greenhouse and particularly by utilizing results from the International Rust Nurseries which are being carried on cooperatively by the United States Department of Agriculture; The Rockefeller Foundation; and Departments of Agriculture, Colleges, and Experiment Stations in many countries throughout the world.

[4] First described on barberry in the greenhouse at St. Paul in 1932.

XIII. Race 7 of Oats Stem Rust Also Explodes in 1950

Although it has not attracted as much attention as race 15B of wheat stem rust, the career of race 7 of oats stem rust is as spectacular as that of 15B. The sudden explosion of race 7 in 1950 changed the status of resistant varieties of oats just as 15B changed that of wheat.

A. The Relation of Race 7 and other Races to Breeding Stem Rust Resistant Oats

The breeding of rust resistant varieties of oats had paralleled that in wheat. There were three principal sources of resistance to stem rust: RICHLAND, WHITE TARTAR (WHITE RUSSIAN), and HAJIRA. All three of these varieties were resistant to the rust races that prevailed in the United States for almost two decades prior to 1940. Several excellent varieties had been obtained from VICTORIA × RICHLAND crosses. But race 8 of oats stem rust increased in the 1940's, and, together with Helminthosporium blight, forced these varieties into virtual oblivion. They were replaced by varieties principally with the WHITE TARTAR resistance to stem rust, which protected them against race 8 and other prevalent races. But two other races, 6 and 7, were making threatening gestures in barberry areas. Race 6 can attack varieties with either of the three types of resistance, especially at high temperature, and race 7 was known to be virulent to WHITE TARTAR. Race 6 has not yet become established independently of barberry, but race 7 declared its independence in 1950. Its history is therefore summarized.

B. The History of Race 7

Race 7 was first reported in North America in 1928, when it was collected in small quantities in Canada (Newton and Johnson, 1944). However, it had been known for some time in Australia (Waterhouse, 1929). The first isolate in the United States was obtained from barberry at Presque Isle, Maine, in 1933 (Stakman and Loegering, 1951). It was not again found in the United States until 1938, when it was isolated from three collections of uredial material from Pennsylvania.

Race 12 is so closely related to race 7 that the two are not clearly distinguishable under all conditions and for practical purposes have sometimes been considered together (Table VI).

It is noteworthy that race 7 had never been widespread and prevalent prior to 1950. Like race 15B, it clearly persisted through the intermediary of barberries. It was found on or near barberries in New York for the seven successive years prior to 1950. Then it almost literally exploded. It was isolated from 54 per cent of the 628 collections of oats stem rust from which

TABLE VI

Record of Races 7 and 12 in the United States, 1933–1949

Year	Remarks
1933	Race 7 first found in United States; one isolate from aecia, Presque Isle, Maine.
1934–1937	Not found.
1938	Race 7, three uredial isolates from Pennsylvania.
1939	Race 7 collected on oats grown near barberry in Pennsylvania and also found in Oklahoma and Wisconsin. One isolate of the closely related race 12 obtained from aecial material collected in Pennsylvania.
1940	Race 12 collected twice from oats in Pennsylvania, in barberry area.
1941	Race 12 collected on barberry in Pennsylvania.
1943	Race 12 collected once on oats in New York and twice in Pennsylvania.
1944	Race 7 collected twice in uredial material in New York and once in Pennsylvania. (In barberry areas.)
1945	Race 7 collected three times in uredial material in Minnesota and three times near barberry bushes in New York.
1946	Race 7 collected twice in Minnesota, once in the fall from Nebraska, three times in New York.
1947	Race 7 collected twice in New York.
1948	Race 7 collected in New York.
1949	Race 7 collected in Kansas,[a] twice in Michigan and once in New York.

[a] Fall collection; not included in published report on physiologic races for 1945–1949.

races were identified in 1950 and comprised 44 per cent of all uredial isolates. Relatively, it was even more prevalent than 15B. The varieties with WHITE TARTAR genes were no longer resistant.

XIV. Shifting Populations of Physiologic Races of Other Pathogens, Especially Crown Rust of Oats

The events described with respect to race 15B of wheat stem rust and race 7 of oats stem rust constitute only one example, although a conspicuous one, of what has happened in the past and of what may happen in the future with these rusts, with other cereal rusts, flax rust, rusts of other crop plants, and many other pathogens, new or previously unknown. Physiologic races of the orange leaf rust of wheat, *Puccinia rubigo-vera* var. *tritici;* of yellow rust of wheat, *P. glumarum* var. *tritici,* and of crown rust of oats, *P. coronata* var. *avenae* have repeatedly become prevalent enough to attack hitherto resistant varieties. This is conspicuously true in the recent history of *P. glumarum* in western Europe and of *P. coronata* in the United states.

For almost two decades it seemed that genes for resistance to crown rust in the varieties VICTORIA and BOND and their derivatives might be adequate protection against the physiologic races then prevalent in North America. But this is no longer true. According to Simons (1956), race 202, to which BOND is susceptible, was the most common race in North America in 1955, comprising 47 per cent of all isolates. Race 258, which attacks VICTORIA, was third in prevalence, with 6.5 per cent of the isolates, and all races that attack VICTORIA comprised 18 per cent of the total; but these races comprised about two-thirds of all isolates identified from the southeastern States of the United States. According to H. C. Murphy, in a special communication to the writers, "Race 216 (and other VICTORIA-attacking races) gradually increased in prevalence in the southeastern States for several years. In 1957 they became established around the Gulf of Mexico and swept up the Mississippi Valley in heavy amounts. VICTORIA derivatives were severely damaged in Texas and northward to Manitoba." Several years ago it appeared that other varieties, such as LANDHAFER and SANTA FE, might be generally resistant (Simons, 1954), but there now are races that attack them also. It seems doubtful whether it will be possible to develop varieties with permanent physiologic resistance against all races of crown rust in North America unless a war of attrition is waged against it by eradicating the alternate host, *Rhamnus* spp., in conjunction with breeding for resistance. Admittedly it would be a long war, as has been true of the combination of barberry eradication and breeding for resistance to stem rusts of oats and wheat, but it seems likely that the chances of ultimate success will be far greater if a two-pronged attack can be made. The problem of developing permanently resistant varieties of cereal grains appears to be further complicated by the evidence of fusion between hyphae of uredial clones whereby new races may be produced (Nelson and Wilcoxson, 1954; Nelson *et al.*, 1955; Bridgmon, 1957; Vakili and Caldwell, 1957, Watson, 1957; Wilcoxson *et al.*, 1957).

XV. A Three-Pronged Attack on 15B and Other Virulent Races of Cereal Rusts

It has certainly become evident from experience with races 56, 15B, and other races of wheat stem rust, with races 7 and 8 of oats stem rust, and with races of crown rust of oats that a permanent solution of cereal rust problems is not easy. It is true that progress has been made during the past 50 years, but it is equally true that the situation has changed repeatedly because too great reliance was placed on varieties that proved to be only temporarily or regionally resistant. There are of course three principal methods by which rust losses can be reduced: (1) The eradication of alter-

nate hosts; (2) the breeding of resistant varieties; (3) the actual or potential use of fungicides. In the past there has been a tendency for the proponents of one or the other of these methods to belittle the importance of the others. Certainly the magnitude of the problem requires that attempts be made to utilize each method to the limit of its potentialities. It seems much more likely that a combination of the three will be much more productive than sole reliance on any one method.

A. Eradication of Alternate Hosts

In evaluating the importance of eradicating alternate hosts in the control of stem rust and crown rust, the role of mutation and heterocaryosis can not be overlooked. It is clear, however, that the races of stem rust of wheat and of oats that were the most catastrophic in their effects on previously resistant varieties, such as races 56 and 15B of the former and 7 and 8 of the latter, were first found on or near barberry bushes and in some cases persisted for a number of years in barberry areas before they became widely established. Indeed, they caused considerable apprehension because of the fact that many physiologic races had increased in prevalence and extended their geographic range either suddenly or gradually. It was suspected, for example, that race 15B of wheat stem rust and races 7 and 8 of oats stem rust would sooner or later declare their independence of barberry and become widely prevalent. It seems very probable that certain other races, such as races 6 and 13 of oats stem rust, which are still found principally on or near barberry bushes, may eventually spread as did the races already discussed.

A national barberry eradication program has been in progress in the United States since 1918, but it is far from complete. In the early years it was widely assumed that the rust might not spread far from barberry bushes. This assumption, however, has proved to be unjustified. Certainly race 15B of wheat stem rust and race 7 of oats stem rust could be said to have been endemic in northeastern United States long before they became prevalent elsewhere. There is evidence from the records of physiologic race surveys of stem rust, made annually by the U.S. Department of Agriculture in cooperation with the Minnesota Agricultural Experiment Station, that the number of races actually decreased in the principal grain-growing areas of the United States as the number of barberry bushes decreased. It is evident now, however, that new or rare races are still being produced on the barberries that remain in the upper Mississippi Valley and particularly on those in the Virginias, Pennsylvania, and New York, and that races not only have spread all over North America from the eastern states but also are likely to do so in future. Although the results of the eradication of the alternate hosts may not become immediately apparent, the effect of eradica-

tion in reducing the number of prevalent races is certain to have a beneficial effect in the long run even if it merely reduces the frequency with which new races become established and lengthens the time required for their establishment. Even local eradication can be expected to have a beneficial effect, although it may not be sufficient to control rust completely. The reduction in the number of physiologic races which can clearly result from eradication of the alternate host will certainly facilitate the production of resistant varieties and lengthen their period of usefulness.

B. Search for Genes for Generalized Resistance

In the past, considerable reliance has been placed at various times on so-called mature or adult-plant resistance. Although many of the presently grown varieties of spring bread wheats can be ruined by race 15B or certain other races, they certainly have more generalized resistance in the field than the spring wheat varieties that were grown fifty years ago. It is known that, in addition to their specialized resistance to individual races, some of these varieties are less easily infected than the varieties that they replaced, that the period of incubation may be longer, that in some cases the individual pustules are smaller, and that some of the varieties may be more tolerant than others in the sense that the same visible amount of rust causes less damage than on certain other varieties. Studies of the individual characters that contribute to this generalized resistance are now being made in several places, notably by a number of investigators under the general supervision of Dr. Helen Hart at the University of Minnesota; and it appears that it may be possible to combine in a single variety a number of characters, each one of which alone may have relatively little effect but which, when combined, may give some measure of protection against all physiologic races. Such characters as waxy bloom of the epidermis, thick epidermis, lignified epidermal cells, few, small, or sluggish stomata, and the amount and disposition of sclerenchyma tissues in the stems may all contribute to generalized resistance. Researches of this type should be continued and amplified.

As it is now known that environmental conditions such as temperature may affect the reaction of varieties to certain rusts, it is of the utmost importance that large and spacious laboratories be established in which it would be possible to control environmental factors on a large scale in order to predetermine the variability in resistance of individual varieties and to determine more precisely the factors affecting the variability. These laboratory buildings should be of the same order of magnitude as covered arenas for sports or as certain of the national atomic energy laboratories.

It should be emphasized again that basic researches on the genetics,

the physiology, and the ecology of crop plants and of rusts, and of the interactions between them, are required if a permanent solution of rust problems is to be attained. Even if no permanent solution is attained, basic researches should at least show the possibilities and limitations within which procedures should be carried out and within which there can be expectations of success. Simply stated, the complete virulence potential and the complete resistance potential of rusts and of crop plants must be determined.

C. Possibilities of Chemical Control

Obviously, the ideal way of controlling rusts is by the development of resistant varieties, if this proves to be feasible and more permanently effective than in the past. It may be necessary in some cases, however, to resort to the use of chemicals even after alternate hosts have been eradicated and after the most resistant varieties possible have been produced. What is needed, of course, is chemical fungicides that can be applied in small quantities and infrequently and that will not only be somewhat systemic in their effects but that have some therapeutic as well as protective value. Enough progress has been made to give some hope that treatment with fungicides may in some cases at least and under some conditions be a valuable adjunct to other methods of control.

XVI. Conclusion

Breeding spring wheats for resistance to stem rust and leaf rusts and other diseases has been in progress in the United States for fifty years. Resistant varieties, including durums, have been grown on a smaller or larger scale and for a longer or shorter period during a period of about forty years immediately following the epidemic of 1916 when durums largely supplanted bread wheats in parts of the spring wheat area. During these four decades, spring wheat has been reasonably well protected against rust in a total of about twenty years. Physiologic races, of which 15B is only one conspicuous example, have repeatedly transferred varieties from the resistant to the susceptible category. Everything possible should be done to reduce the number of physiologic races through eradication of alternate hosts. In addition, extensive surveys must be continued in order to anticipate as much as possible the upsurge of dangerous races. The base of resistance in crop plants must be broadened. This requires a world-wide search for all of the genes that affect resistance directly and indirectly. Potential parents and hybrids must be much more widely and intensively tested than in the past. This will require a continuation and

amplification of world-wide testing programs and of intensive studies in adequate field laboratories provided with facilities for controlling environmental conditions. The possibility of inducing desirable mutants by mutagenic agents such as radiations and chemicals should be thoroughly tested. Obviously all possible methods of rust control should be mutually supplemental: the eradication of alternate hosts, the breeding of resistant varieties on an adequate scientific basis, and a thorough investigation of the possibilty of new and effective fungicides.

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AUSTRALIAN SOILS AND THEIR RESPONSES TO FERTILIZERS

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I. Introduction

Artificial fertilizers have been used in Australia for about seventy years and have produced some of the most spectacular crop and pasture responses in the world. These responses have been given by phosphatic fertilizers, and by the trace elements copper, zinc, molybdenum, manganese, boron, and iron. In addition, copper and cobalt have been widely used to correct nutritional disorders in sheep and cattle. This has been done directly with licks and indirectly through additions to the pasture. These nutrients, phosphorus and the trace elements, have focused both local and overseas attention on the use of artificial fertilizers in Australia. More recently, potassium and sulfur have assumed increasing importance. Nitrogen, though moderately to acutely deficient throughout most of Australia, is as yet little used as a commercial fertilizer, except on sugar cane and horticultural crops.

Great economic significance has attached in recent years to the combined use of superphosphate and one or more of the trace elements to develop sown pastures based on various clover species, especially subterranean clover, on vast tracts of land in southern Australia. Formerly these areas, lying in regions of moderate to high rainfall, were considered almost sterile and worthless. They are now being converted to soils of satisfactory productivity by what is possibly the most extensive fertility-building program in the world. There is wide interest in the physical and chemical characteristics of the soils and in the geochemical, climatic, and biological circumstances which have led to such extreme nutritional deficiencies. Herein is given an account of Australian soils, especially of those on which marked deficiencies have been recorded, together with selected agonomic data on crop and pasture responses. An introductory section briefly describes the climate and land use.

II. The Climate and Land Use of Australia

Australia, with an area of almost three million square miles, lies between latitudes 11° S and 43° S, a span corresponding to that from Costa Rica to Detroit or from Nigeria to southern France. Its size gives a great range of climates with a correspondingly varying pattern of land use.

Australia is an island continent of low relief, the most notable topographic feature being the Great Dividing Range running from Cape York in the north, southward through the eastern states and swinging westward across Victoria. The general level of the Range is not great, much of it being tableland of 2,000–3,000 feet, with Mount Kosciusko, the highest peak in the country, reaching 7,328 feet. Despite its moderate altitude, this range, some 2,000 miles in length, exercises a major influence over the climate, soils, and land use of eastern Australia. It is in the environs of this range that agricultural production and population density are greatest.

Much of the western half of Australia is a vast and for the most part featureless plateau of 1,000–1,500 feet elevation. Over most of its area this plateau has little influence on precipitation. Much of it receives only sporadic rain-bearing winds and has a semiarid or desert climate. Extreme aridity with about 4 inches rainfall per year is a feature of the depression around Lake Eyre, which lies below sea level in the central region.

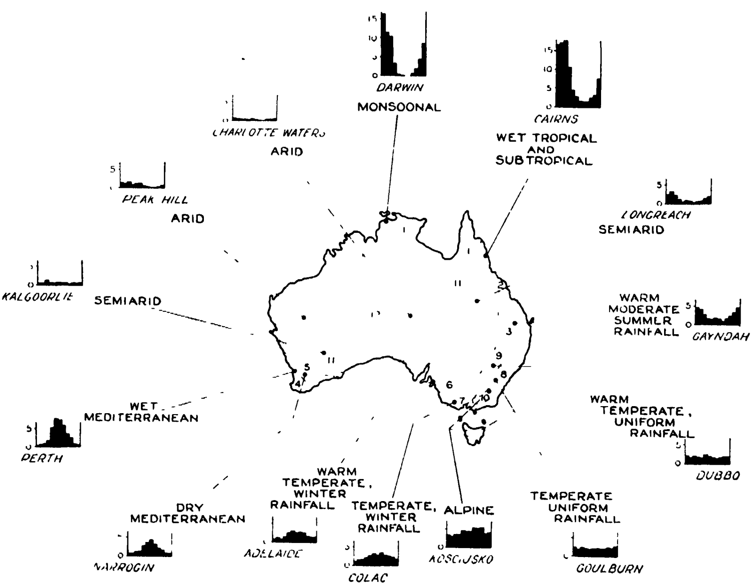

FIG. 1. Climatic regions of Australia with rainfall histograms for selected stations.

Of the lesser topographic features, the Mt. Lofty and Flinders Ranges running northward from Adelaide in South Australia, are of considerable importance. These ranges influence the climate and agriculture of many thousand square miles of that state.

Superimposed on this relatively simple topographic pattern are the major climatic influences characteristic of these latitudes (Figs. 1 and 2). Across the north, tropical low pressure systems bring heavy summer rainstorms, but rainfall (30–60 inches per year) is confined to a three to four month season. The short rainfall season and high temperature impose serious limitations on agricultural and pastoral activity in this monsoonal region. Extensive cattle stations (ranches) are virtually the exclusive form of land use; the cattle graze the rapid growth of tropical tall pastures in the wet season and the very poor quality protein-deficient dry pasture for the remainder of the year. Agriculture is insignificant, with a few peanut farms along the river levees and a very recent semi-experimental production of rice on wide alluvial plains subject to flooding (Zone 1 in Fig. 1).

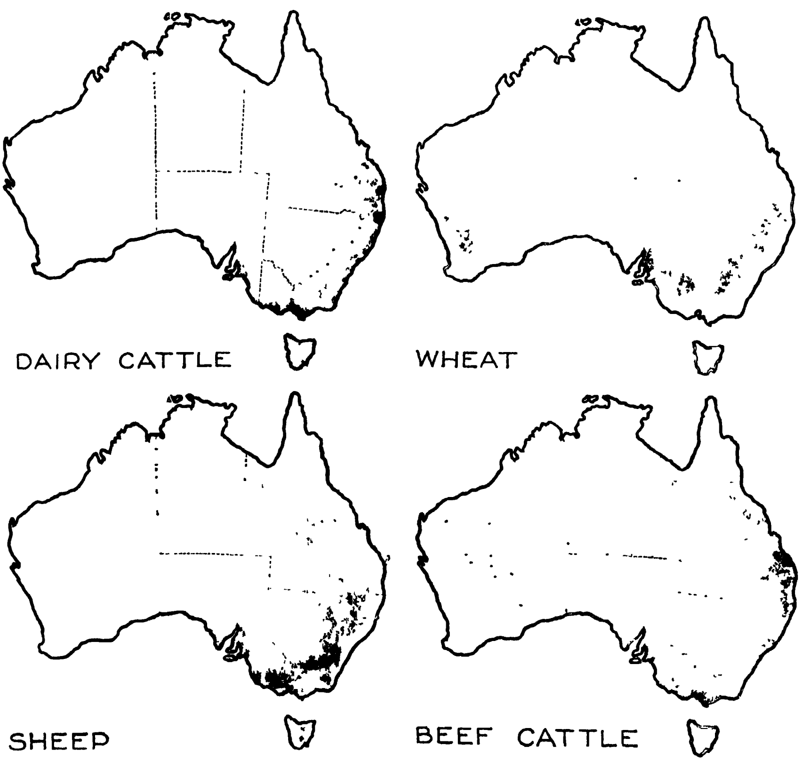

FIG. 2A. Land use maps of Australia.

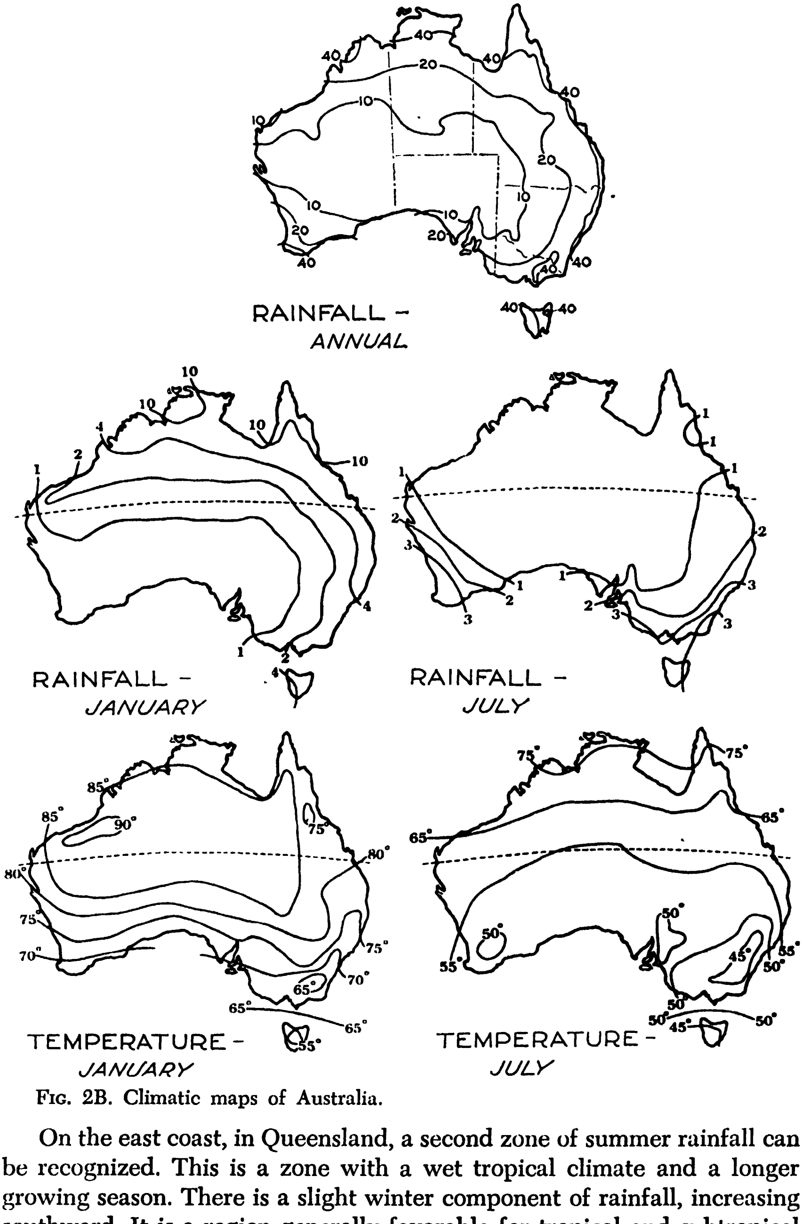

FIG. 2B. Climatic maps of Australia.

On the east coast, in Queensland, a second zone of summer rainfall can be recognized. This is a zone with a wet tropical climate and a longer growing season. There is a slight winter component of rainfall, increasing southward. It is a region generally favorable for tropical and subtropical

crop and stock production, with sugar production, dairying, beef cattle, and tropical fruits as the main activities (Zone 2). In a subcoastal belt of lower summer rainfall beef cattle production is the principal industry (Zone 3).

Across southern Australia there lies a region subject to the influence of polar front rain. This affects the southern half of the continent in the winter, but only the most southerly regions of the southeast of Australia in the summer. Especially in the southwest of western Australia this gives a Mediterranean-type climate, with mild, wet winters and hot, dry summers. This region (Zones 4 and 5) is almost exclusively devoted to the culture of winter annual crops, especially pasture plants of Mediterranean origin (Zone 4) and of wheat (Zone 5).

In the south of South Australia and in Victoria the rainfall again shows a marked winter peak, but here there is an appreciable summer rainfall component (Zones 6 and 7). Nevertheless the agriculture remains essentially of Mediterranean character, with wheat, barley, vines, and winter annual pasture plant predominant. Dairying is important in Zone 7.

In the west of the continent, the summer and winter rainfall zones show only occasional and erratic overlap and are thus separated by sparsely occupied pastoral country. In the east, however, the influence of humid masses of Pacific air in the summer and the effects of the Great Dividing Range cause northern and southern rainfalls to overlap to give an extensive region of approximately uniform rainfall distribution, though with a summer maximum in the north of the zone and a winter maximum in the south. In this southeast sector of Australia lies the greatest concentration of cropping, livestock production, and human population. The Dividing Range further subdivides this region; one may recognize a coastal plain of narrow but greatly varying width, the tableland of the Divide itself with substantially lower temperatures (together comprising Zone 8), and the inland slopes toward the interior plains (Zone 9). Dairying and mixed farming reach their greatest development in the coastal areas. Sheep raising is the principal industry of the tableland. On the inland slopes lies a great arc of wheat production, extending from the Darling Downs of southern Queensland through New South Wales and Victoria into South Australia. (Zones 6 & 9) The Southern Alps around Mount Kosciusko (Zone 10) and the mountains of western Tasmania are mainly rugged, timbered country, sparsely used for summer grazing.

Finally there are the dry areas of inland Australia. Inward from the several zones already described lies a semiarid region (Zone 11) devoted solely to stock raising, principally cattle in the north and sheep in the south and east of the Zone. Properties are large, rainfall is erratic, and

production is subject to the hazards of prolonged drought. Property management is related to such problems as stock water supply, stock movement and transport, and in some sectors, increased provision of fencing. The use of fertilizers is unknown and likely to remain so except where irrigation is practiced, as in the Murray River basin.

This semiarid zone extends inland almost to the limit of settlement, where it fringes on the desert (Zone 12). Grazing is practiced in the more favorable areas, such as the Alice Springs region, but much of the arid zone appears unsuited to any permanent settlement.

This brief account necessarily ignores the great multiplicity of local climates and local land uses within each of the zones. It is presented as a broad background to the account of the soils and the geographic pattern of the use of fertilizers.

III. The Australian Soil Landscape

A. Petrology and Geomorphology

A natural consequence of the vast area of Australia is the great diversity of parent materials and the wide range of climates involved in the soil forming processes. Parent materials vary from the most siliceous sedimentary and igneous rocks, alluvia, and aeolian sands to limestones, calcareous sands, and basic igneous rocks and their alluvial derivatives. Hence the range of soils is great and extends from the dry soils of desert sand ridges to podzols and moor peats of the excessively wet areas. These features alone, however, do not particularly distinguish Australia pedologically from other continental masses.

On the other hand Australia has several distinctive geomorphic characteristics which together have conferred somewhat unique features on the soils of the continent.

First, it is characterized by limited uplift. In consequence there has been very modest dissection and less than normal exposure of basement rocks to juvenile weathering. A corollary of this is the survival of widespread areas of late Tertiary and Pleistocene land surfaces which extend from the arid regions to the most humid areas. On these are preserved to varying extent soils with obviously senescent features. Thus there is not only a great range in the age, parent materials, and climatic environments of Australian soils, but also an unusually high proportion of soils of great antiquity.

Second, Pleistocene glaciations and periglacial conditions were confined to the southeastern corner of the mainland and to Tasmania so that dissection and exposure of new surfaces due to these agencies was extremely

limited. Deposition of morainic materials and loess was almost negligible.

Third, the only notable areas of vulcanism are found in a relatively narrow zone extending along the eastern seaboard and for a short distance inland. Those occurrences include volcanic ash and basalt of Tertiary to mid-Recent age. All volcanoes are now extinct.

Thus within the Australian array of soils there is a notable proportion of old, leached, and therefore impoverished soils. These have morphological features very distinct from those found on more recent landscapes. Thus for a clear understanding of Australian soil geography it is necessary to approach the subject by way of a geomorphic analysis. Otherwise the occurrence in relatively dry climatic zones of some soils with atypical morphological features such as extremely marked texture contrast, great depth, profound bleaching and mottling, and masses of lateritic and secondary siliceous materials in the profile will appear anomalous.

The Great Dividing Range is one of the most dissected landscape features. It presents a considerable range of parent materials on its slopes and in the areas of alluvium laid down by its effluent streams. Thus it has a profound influence on the soil pattern of the eastern part of the continent, both on the sedentary soils of the coast and ranges and on the vast alluvial formations to the westward, the plains of the Murray, Murrumbidgee, Darling, and Diamentina river systems. These rivers in their long sluggish courses differ markedly from the short fast streams which flow to the Pacific coast and which have deposited only limited amounts of alluvium.

Except for lesser mountainous areas such as the Mount Lofty and Flinders Ranges in South Australia, the Musgrave and Macdonnell Ranges in the desertic center, and the rugged ranges of the Kimberley and Arnhem Land regions of northern Australia, alluvial formations and subdued weathered surfaces characterize the topographic landscape throughout the rest of the continent and give the impression of a vast plain with only minor features rising above it.

Even in the more dissected parts of the Great Dividing Range it is not difficult to identify topographical elements of old land surfaces. In the areas of gentler relief, both on the Divide and in the lesser ranges, there is clear pedological as well as topographic evidence of such surfaces. These surfaces range from deeply weathered lateritic podzolic soils and red earth mantles on fragmented Pliocene peneplains, to lower situated flights of Pleistocene terraces with arrays of less and less mature soils, down to the recent floodplains.

Evidence of Tertiary surfaces on the extensive plains is abundant, for flat topped residuals, more or less covered by soil remnants, are frequently the only prominent topographic features. These residuals vary in size from extensive tablelands many square miles in area to small abrupt-sided, tent-

shaped hills with sharply or gently sloping beveled edges where the present cycle of geologic erosion is gradually consuming the old land surface. These remnants of former peneplains, sometimes slightly tilted, occur throughout the continent. They occur from the most arid part of the extensive desert areas to the humid, coastal, and subcoastal regions of the southwest and east, and to the island of Tasmania. Often there is clear evidence of several such surfaces, separated, especially in the arid regions, by sharp but small erosion escarpments, and in the more humid regions delineated by more complex but smoother slopes. In addition there is sound geological evidence that at least some of these old surfaces have been fragmented by faulting. This has been demonstrated, for example, by Sprigg (1945) for the Mount Lofty Ranges in South Australia. He found that systematic block faulting has cleaved a Pliocene land surface with its lateritic podzolic soil mantle into a broad stepped formation reaching at its maximum an elevation of about 2,000 feet. Much of the old lateritic surface is relatively intact on the gently undulating surface of the steps. Newer surfaces with sedentary podzolic soils on exposed Pre-Cambrian rocks occupy the steeply sloping fault escarpments.

In some localities all that remains of the old peneplain are small conical hill or vestigial smears or sheets without any of the original lateritic surface and composed of remnants of the deeper seated kaolinitic horizons of the laterite profile. This kaolinitic material is widely exposed on the beveled surfaces of the more gently dissected residuals in the moster areas where the incisions of the dismembering streams have been wide and shallow, as shown by Stephens *et al.* (1942) for the Cressy-Longford district in Tasmania. In other areas the only evidence of the old surface is a general concordance in the heights of hilltops and sometimes the occurrence of antecedent stream courses inherited from the senescent drainage pattern of the old peneplain. In such localities, the undulating surface and its sedentary soils are being influenced by the present weathering and erosional cycle.

The nature and fate of the detrital material from the dismembering of the ancient surfaces is of particular interest, for it in part determines the character of the parent material of the soil in the depositional zones. The detritus from the earlier and shallower dissections was more weathered and leached than that from later and deeper dissections which reached down into the newly weathered parent rock. Varying proportions of old and new material characterize the deposits on which soils of the Pleistocene and Recent have formed, the older material generally being the more impoverished. These materials with their subsequently developed soil profiles, are preserved on the landscape to a very variable degree as flights of terraces or, in aggrading situations such as occur west of the Great Divide,

as repeatedly buried deposits. Some of the terraces, especially in the arid regions, were in fact very extensive depositional plains. Today, with their Pleistocene soils more or less modified by subsequent geomorphic and pedologic events, these plains dominate parts of the landscape.

Much of the immediate coastline and hinterland of southern Australia has abundant dune formations of Pleistocene and Recent age. The older dunes have been leached of their content of shell lime and the resulting highly siliceous sand has been redistributed as dunes and sand sheets. In places adjacent to the littoral this has been augmented by coarse textured deposits associated with the short coastal streams. These materials singly or in combination are extremely porous and even under quite moderate rainfalls have been extremely podzolized. These soils and the lateritic podzolic soils of the extensive tableland remnants unquestionably represent the poorest soils in Australia on which economic plants have been grown.

Australian as well as overseas evidence indicates that the Pliocene was a period of variable but predominantly warm humid climate, that the Pleistocene was more variable, cooler and generally moist, and that the Recent has been a period of increasing aridity and rising temperatures with some possible emphasis in aridity about 5,000 years ago. Hence, not only do the older soils of the Pliocene and Pleistocene exhibit clear evidence of being more leached because of the moister condition under which they were formed, but also their greater age means that there has been a progressive if somewhat interrupted cumulative effect of that leaching due to several wet periods since their initial formation. Hence it should be no surprise to find extremely leached and differentiated soils on old land surface residuals and on terraces and plains in areas where the present day climate is more consistent with soils of higher base status and less contrasting horizon development in the soil profile.

Two other features have had a profound effect in widening the array of Australian soils beyond that associated with climate and its weathering and leaching effects. These are, first, the frequent accumulation in soils of saline materials and the incidence of associated post-saline effects, and, second, the occurrence of parent materials such as limestone and basalt which react to the leaching factor in a manner distinctively different from that displayed by the usual siliceous and feldspathic rocks.

Southern Australia especially is noted for a prevalence of soils showing solonetzic features. They occur over a fairly wide climatic range, often lying alongside podzolic soils or intermingled with them. Although the solonetz and solodized solonetz soils are easy to recognize, the solodic forms are not very distinctive from some of the podzolic soils. In fact, on the basis of profile morphology and analytical data (Sections VI, C and VII, D) we

must suspect that some of these soils have suffered both solodization and podzolization either operating simultaneously (Hubble, 1946; Stephens, 1951) or succeeding one another on the occasion of climatic or drainage changes. Since they occur on both Tertiary and Quaternary landscapes a number of such combinations or successions are possible.

In the semiarid zones of southern Australia there also occurs a vast area of distinctive calcareous soils subject to the effects of salt accumulation. These, formerly called mallee soils, are the solonized brown soils. They contain large quantities of calcium carbonate, which is presumed in some areas at least to be of loessial origin. The distribution of the lime in the profile and its form as sheets, crusts, and nodules as well as powdery forms is reminiscent of the "caliche" of North America and the "croute calcaire" of North Africa.

Other soils associated with limestone formations in the humid and subhumid areas comprise the usually well drained calcareous aeolian sands, terra rossa, brown forest, and rendzina soils and where water tables are involved, ground water rendzina and fen peats. In drier areas occur gray calcareous soils, obviously related to rendzina, and in still drier regions, gray-brown and red calcareous desert soils.

Though basalt is largely confined to the eastern coastal region, there are many separate occurrences of varying size extending from northern Queensland to Tasmania. These have given rise to sedentary soils of great depth and striking red color, while in drier inland areas the soils are black clays. Krasnozems, the red soils which formerly carried a dense forest and are extremely well structured and porous, are now practically entirely cleared for intensive agricultural pursuits. Together with closely similar red soils on other rocks in the tropical portion of the coastal region, they show a remarkably consistent morphological expression over the wide climatic range associated with a 25° spread of latitude.

B. The Relationship of Genetic Factors to the Fertility of Australian Soils

The data presented in the previous section show that the prevalence of soils of low fertility in Australia may be attributed in large measure to their age, their parent materials, and to podzolizing and solonizing influences. Specific factors contributing to the occurrence of poor soils are:

(a) The large areas of Tertiary soils such as the extremely leached lateritic podzolic soils and red earths.

(b) The prevalence of newer soils developed *in situ* on lower horizon remnants of the above soils and on their colluvial and alluvial residues. As Thorp (1949) in annotating the Australian work on lateritic soils remarked, "New soils from old ones, in this instance, are poor indeed."

(c) The extreme susceptibility of several soil groups to leaching under present-day climatic conditions. The highly flocculated krasnozems, the aeolian and fluviatile sands, and the soils developed on coarse-textured sedimentary rock all show great porosity and all occur extensively in regions of moderate to high rainfall.

(d) The continuous solonizing influence of cyclic salt characteristic of Australian rainfall. This has given rise to large areas of solodized solonetz and solonized brown soils and has impressed a solodic character on many of the podzolic soils.

(e) The large proportion of lime in the calcareous aeolian sands and in the extensive solonized brown soils. This high lime status limits the availability of several of the trace elements.

(f) The large proportion of coarse-textured sedimentary soils, high in silica and low in phosphorus, which form the parent materials of many Australian soils. The cycles of weathering through which the parent materials have already passed greatly reduce their prospect of giving rise to fertile soil. In addition some of the igneous rocks, such as the dolerites of Tasmania (Edwards, 1942), are low in phosphorus.

It is of interest to examine the extent to which soil and agronomic investigations in Australia have permitted definition of the relationship between the occurrence of mineral deficiency of plants or animals on the one hand, and the parent material, age, and present day profile of the soils.

As shown by Tables I and II which summarize the incidence of deficiencies on the great soil groups, there is a broad relationship between soil and deficiencies. Some of these deficiencies are specific to soil properties which are themselves characteristic of the great soil groups. Examples are the positive and negative correlation between pH value and sulfur and molybdenum deficiency, respectively. Broadly, we can note the high incidence of deficiencies on certain soil groups, such as the podzolic and lateritic podzolic soils, the absence of copper deficiency on red-brown earths, and so on.

It may be asked, however, whether the relationship between soil profile and the deficiency of a particular element is such as to permit confident prediction of deficiencies by extrapolation of experience from one occurrence to another within a particular soil group. The answer must be: "To a varying extent depending on the element, yes, but not with great confidence except in the case of the degree of phosphorus deficiency." Confidence increases at lower classificational levels such as Soil Series and Types.

It is of interest to quote some examples. Molybdenum deficiency was first recorded on a lateritic podzolic soil in South Australia. This experience was immediately and successfully extrapolated to similar soils in Tasmania, but attempts on lateritic podzolic soils in Western Australia, with minor

TABLE I

Record of Responses to Fertilizers on Australian Soils

Soils	Fertilizer				
	Phosphorus	Potassium	Sulfur	Magnesium	Lime
Alluvial soils	Practically all crops respond strongly	Pastures, NSW Sugar, Q Oats, T Flax, T		Citrus, Q	Peas, T
Calcareous aeolian sands	Practically all crops respond strongly	Lucerne, SA Potatoes, T			
Acid swamp soils	Practically all crops respond strongly	Potatoes, SA, WA			Sub-clover, SA, WA Vegetables, WA
Podzols and ground-water podzols	Practically all crops respond strongly	Pastures, NSW, V, T *Pinus radiata*, T			*Trifolium* spp., V, WA, T
Lateritic podzolic soils	Practically all crops respond strongly	*Trifolium* spp., SA, WA, T Flax, T	Sub-clover, WA	Apples, WA Citrus, WA	Pastures, NSW Sub-clover, SA
Gray-brown, brown, red and yellow podzolic soils and meadow podzolic soils	Practically all crops respond strongly	*Trifolium* spp., SA, WA, T Pastures, NSW, V, T Vegetables, V, WA Lucerne, SA *Pinus radiata*, T Fruit trees, V Potatoes, V, SA, WA, T Peanuts, Q	Pastures, NSW, T Plums, Q Sub-clover, SA, WA	Pastures, NSW Vegetables, NSW Citrus, NSW, V, Q Pome fruits, V	Peanuts, Q Potatoes, T Pastures, NSW, V *Trifolium* spp., NSW, V, SA, T Lucerne, Q, SA Vegetables, V Flax, V
Krasnozems	Small to moderate response	Pastures, NSW Sugar, Q Vegetables, V Peanuts, Q Fruit trees, V Potatoes, VT	*Trifolium* spp., NSW	Pastures, Q	Pastures, NSW, Q Lucerne, NSW *Trifolium* spp., T Potatoes, T Peas, T

TABLE I—Continued

Soils	Fertilizer				
	Phosphorus	Potassium	Sulfur	Magnesium	Lime
Lateritic red earths	Practically all crops respond strongly				Lucerne, Q Vegetables, Q
Terra rossa	Practically all crops respond strongly				
Black earths	Nil to moderate response		*Medicago* spp., NSW Lucerne, Q Grasses, Q		
Rendzinas and ground-water rendzinas	Practically all crops respond strongly				
Fen soils	Practically all crops respond strongly				
Solodized solonetz solods	Practically all crops respond strongly		Pasture, NSW		
Solonized brown soils	Practically all crops respond strongly				
Red-brown earths	Practically all crops respond strongly			Citrus, V	Pastures, NSW
Gray calcareous soils	Practically all crops respond strongly				
Gray and brown soils of heavy texture	Practically all crops respond strongly				

NSW = New South Wales and includes the Australian Capital Territory, V = Victoria, Q = Queensland, SA = South Australia, WA = Western Australia, T = Tasmania, Sub-clover = Subterranean clover.

TABLE II

Records of Responses to the Trace Elements on Australian Soils

Soil	Trace element						
	Copper	Cobalt	Zinc	Molybdenum	Manganese	Boron	Iron
Alluvial soils			Citrus, Q			Vegetables, NSW Citrus, Q	
Calcareous aeolian sands	*Trifolium* spp., V, WA, T Lucerne, SA, T Annual medics, SA Lupines, WA Cereals, SA, WA Cattle, V, SA, WA, T Sheep, V, SA, WA, T	Cattle, SA, WA, T Sheep, SA, WA, T	*Trifolium* spp., V, T Lucerne, SA Annual medics, SA Oats, SA, WA	Cauliflowers, WA	Annual medics, SA Oats, SA		
Acid swamp soils	Sudan grass, Barley, maize, peas, Potatoes, swedes, Tomatoes, cattle, Sheep } WA			Cauliflowers, WA	Vegetables, V	Sub-clover, T	Sub-clover, WA Oats, WA
Podzols and ground-water podzols	*Trifolium* spp., NSW, SA, WA, T Pome fruits, V Cattle, WA, T Sheep, WA, T	Cattle, WA Sheep, WA	*Trifolium* spp., SA, T *Pinus radiata*, SA, WA, T Apples, T		Apples, T	Sub-clover, T Apples, T	
Lateritic podzolic soils	*Trifolium* spp., SA, WA Lupines, cereals, Citrus, plums, Apples } WA Cattle, WA, T Sheep, WA, T	Cattle, WA Sheep, WA	Sub-clover, SA, WA Ryegrass, cereals, Pome fruits, flax, *Pinus radiata* } WA	*Trifolium* spp., SA, T Crucifers, SA, WA Peas, T Oats, T	Sub-clover, SA, WA Cereals, WA Apples, WA	Lucerne, NSW	
Gray-brown, brown, red, yellow and meadow (gley) podzolic soils	*Trifolium* spp., NSW, V, Q, SA, WA, T Lupines, cereals, Vines } WA Apples, WA, T Citrus, NSW Pears, SA Tobacco, Q Cattle, V, T Sheep, NSW, V, T	Cattle, WA, T Sheep, WA, T	*Trifolium* spp., NSW, V, Q, SA Citrus, NSW, Q, WA Pome fruit, V, SA, T *Pinus radiata*, V, SA, WA	*Trifolium* spp., NSW, V, Q, SA, WA, T Crucifers, Q, SA, WA, T Vegetables, NSW Flax, V Tobacco, Q Rockmelons, WA Peas, T	Cereals, V Citrus, NSW, V, SA Apples, V, SA, WA, T Stonefruits, V, SA Vegetables, NSW, V	*Trifolium* spp., NSW, Q Apples, NSW, V, T Crucifers, NSW, Q, SA, WA, T Root crops, Q Tomatoes, Q Vines, Q Celery, WA	Citrus, Q Tomatoes, Q Apples, Q Vines, Q
Krasnozems	*Trifolium* spp., NSW Cattle, NSW, T Sheep, T	Cattle, T Sheep, T	*Trifolium* spp., NSW	*Trifolium* spp., NSW, V, T Peas, oats, T		Lucerne, NSW Apples, NSW Pasture, NSW	Pineapples, Q
Lateritic red earths				Crucifers, Q		Rootcrops, Q Cauliflowers, Q	Pineapples, Q

TABLE II—Continued

Soil	Trace element: Copper	Cobalt	Zinc	Molybdenum	Manganese	Boron	Iron
Terra rossa	*Trifolium* spp., SA, T Lucerne, SA Cattle, T Sheep, T	Cattle, T Sheep, T	Sub-clover, SA		Sub-clover, SA Annual medics, SA Cereals, SA		
Black earths	Sheep, NSW, Q Cattle, Q		Flax, V Linseed, NSW, Q	Sub-clover, SA Crucifers, T	Vegetables, V Stone fruits, T		Peaches, T
Rendzinas and ground-water rendzinas	Sub-clover, SA Cattle, SA Sheep, SA	Cattle, SA Sheep, SA	*Trifolium* spp., SA Phalaris, SA		*Trifolium* spp., SA Annual medics, SA Cereals, SA Phalaris, SA		
Fen soils	*Trifolium* spp., SA Lucerne, SA Barley, maize, Swedes, potatoes, Peas, tomatoes } WA Cattle, T Sheep, T	Cattle, T Sheep, T	*Trifolium* spp., SA Phalaris, SA Lucerne, SA		White clover, SA Peas, WA Potatoes, WA Swedes, WA		
Solodized solonetz and solods	Sub-clover, SA Lucerne, SA Cereals, SA Sheep, SA	Sheep, SA	Sub-clover, V, SA Cereals, SA	*Trifolium* spp., V	Sub-clover, SA Oats, SA		
Solonized brown soils	Pears, SA Citrus, SA Sheep, SA	Sheep, SA	Sub-clover, SA Citrus, SA, NSW Pome fruits, SA Stone fruits, SA		Citrus, SA		Citrus, V, SA Stone fruit, V, SA Vines, V
Red-brown earths			Citrus, NSW, V Pears, V Peaches, V Vines, SA	Pasture legumes, NSW	Citrus, NSW		Stone fruits, NSW, SA Citrus, SA
Gray calcareous soils			Sub-clover, SA Flax, SA		*Trifolium* spp., SA, T Annual medics, SA Cereals, peas, Stone fruits, SA		
Gray and brown soils of heavy texture	Sheep, Q Cattle, Q		Sub-clover, V, SA Cereals, V, SA Citrus, NSW Flax, V, SA Vines, SA				Stone fruits, V

NSW = New South Wales and includes the Australian Capital Territory. V = Victoria Q = Queensland, SA = South Australia, WA = Western Australia, T = Tasmania, Sub-clover = Subterranean clover

exceptions, proved negative. The key to the difference between these separate areas of lateritic podzolic soils still remains to be found.

In distinct contrast, there is the consistency of response to copper and cobalt on the calcareous aeolian sands of southern Australia, following the initial work at Robe, South Australia. It can be said that the finding of these deficiencies on a particular occurrence of this soil group permitted the prediction, later confirmed, that all soils of this group were likely to be affected in greater or less degree.

Over much of the continent, however, the intimacy of the relationship of soil and deficiency is insufficiently indicated by study either of the profile or by soil analysis, for there are some considerable variations in the presence of the trace elements in some of the great soil groups (Table III).

McLachlan (1955) examined the phosphorus, sulfur, and molybdenum responses of soils collected from a wide area of eastern Australia. He found no significant correlation between the occurrence and intensity of the deficiency of one element and the deficiency of either of the others, nor any correlation between deficiency and parent material (basalt, granite, sedimentary rock), soil color, organic matter, or texture. He did however find a greater mean response to phosphorus on red and yellow podzolic soils than on black earths, with red earths in an intermediate position. Sulfur and molybdenum deficiency were related to soil groups to the extent that they showed positive and negative correlation, respectively, with rising pH. Results of this kind are altogether too complex to enable confident prediction of responses based on soil descriptions.

Indeed most deficiencies in Australia have so far been determined by agronomic and animal health trials using all possible treatments. Treatments used have been based on plant and animal symptoms, on plant analyses (e.g. the decision to test for molybdenum deficiency when this element was first recorded was based on spectrographic analysis of plant material) and to a lesser degree on the experience with similar soils elsewhere. Soil and geomorphic surveys have proved of greater value in defining the geographic limits of particular records of response than in permitting confident forecasts of response in other regions of the continent.

Although the soil group has some limitations in revealing probable fertilizer response, a notable example of the influence of common genesis on mineral deficiency may be quoted. In the southeast of South Australia there are calcareous dunes, water-table rendzinas, ridges of deep sandy podzolic soils, and terra rossa soils all showing a more or less common set of deficiencies, involving phosphorus, cobalt, copper, zinc, and manganese (Tiver, 1955). It is known that all have been formed in the course of the gradual seaward retreat of the shoreline from a late Pliocene coast, and all are derived by different processes of varying duration (Stephens,

TABLE III

Content of Trace Elements in Australian Soils by Spectrographic Analysis[a]

Soils		Cu (ppm) Range	Cu Mean	Cu No. of samples	Co (ppm) Range	Co Mean	Co No. of samples	Zn (ppm) Range	Zn Mean	Zn No. of samples	Mo (ppm) Range	Mo Mean	Mo No. of samples	Mn (ppm) Range	Mn Mean	Mn No. of samples	Fe (%) Range	Fe Mean	Fe No. of samples
Alluvial	A	10–23	16	(3)	1.5–8	3.8	(3)		265	(1)	3.5–7	5.8	(3)	100–1000	490	(3)		5.7	(1)
	B		2	(1)		7	(1)		92	(1)		3.5	(1)		700	(1)		5.1	(1)
Calcareous aeolian sands	A		2	(1)															
Podzols and ground-water podzols	A	2.8–3.5	3.0	(4)		<2	(4)	5–9	6.7	(4)	2–2.8	2.2	(4)	3.3–7.2	5.4	(4)	.029–.036	.032	(4)
	B	3.0–3.8	3.5	(4)		<2	(4)	5–8	7.0	(4)	3.1–3.6	3.3	(4)	6.3–12	9.2	(4)	.31–.58	.42	(4)
Lateritic podzolic soils	A	0.5–39	8.5	(11)	All <2	~2	(8)	7–39	19	(8)	<2–12	6.1	(9)	<5–1200	500	(9)	<.1–4.4	2.4	(8)
	B	0.8–69	12	(9)	<2–12	~2	(7)	7–160	47	(7)	4–21	9.6	(8)	10–1000	400	(8)	0.3–18	6.7	(7)
Podzolic soils	A	3.3–57	12.3	(13)	<2–15	~2	(7)	12–27	18	(6)	<2–5.5	3.4	(13)	5–820	213	(13)	0.8–4.2	2.1	(5)
	B	4.4–210	44	(12)	<2–34	~10	(6)	14–44	22	(5)	<2–7.0	4.3	(12)	5–700	157	(12)	1.7–6.8	4.4	(4)
Krasnozems	A	22–130	64	(8)	4–73	20	(8)	25–90	61	(3)	3.5–16	11	(7)	280–2000	1140	(2)	2.7–8.3	5.5	(2)
	B	49–140	86	(3)	7–120	52	(3)	27–125	76	(2)	8.4–13	11	(3)	160–1300	730	(2)	12.7–13.2	13	(2)
Terra rossa	S[b]	29–65	47	(6)	10–30	22	(6)	50–86	63	(6)	4.8–8.5	6.5	(6)	520–1400	910	(6)			
	SS	25–66	39	(6)	9–31	22	(6)	39–79	62	(6)	4.1–8.3	6.5	(6)	440–1000	770	(6)			
	S[c]	2.2–9.6	5.4	(4)	<2–15	6	(4)	11–24	19	(4)	<2–5.5	3.2	(4)	180–1200	700	(4)			
	SS	2.0–8.1	4.4	(4)	<2–15	6	(4)	9–27	17	(4)	<2–5.6	3.6	(4)	140–920	510	(4)			
Rendzinas and ground-water rendzinas	S[a]	15–43	29	(5)	6–18	11	(5)	27–67	44	(5)	5.1–7.1	6.1	(5)	400–550	470	(5)			
	SS	12–64	32	(5)	6–27	13	(5)	26–69	50	(5)	4.9–7.8	6.7	(5)	450–650	530	(5)			
	S[b]	6.8–12	9.0	(4)	<2–12	4.4	(4)	18–70	34	(4)	3.6–4.4	4.0	(4)	180–1100	450	(4)			
	SS	5.0–8.3	7.3	(4)	<2–16	7.1	(4)	16–38	25	(4)	3.9–5.2	4.5	(4)	170–1300	480	(4)			
Fen soils	A		5	(1)															
Solodized solonetz and solods	A	7–19	11	(5)							<2–3.3	<2	(5)	5–22	14	(5)			
	B	6–8.5	6.5	(5)							<2–2.5	<2	(5)	5–42	18	(5)			
Solonized brown soils	A	5.3–20	11.5	(6)							<2–3.2	~2	(6)	5–110	53	(6)			
	B	6.5–40	18	(6)							2.5–4.4	3.3	(6)	6–70	22	(6)			
Red-brown earths	A	12–63	29	(16)	<2–23	7.3	(15)		36	(1)	1.5–4.1	3.0	(15)	240–910	520	(15)			
	B	24–85	55	(14)	4.5–15	11	(14)				3.2–4.7	4.0	(14)	180–980	470	(14)			

No information is available for: acid swamp soils, lateritic red earths, black earths, gray calcareous soils, gray and brown soils of heavy texture.
A = A horizon values B = B horizon values S = Surface soil values SS = Subsurface soil values
[a] Compiled by R. M. McKenzie, Spectrographic Group, Division of Soils, C.S.I.R.O. [b] Adelaide area. [c] Southeast of South Australia

1951) from the calcareous dunes or from the underlying and closely related Miocene limestone. Twenty-five years ago no soil worker or agronomist would have predicted that soils so different in texture, depth, and natural fertility would prove to be so closely linked in their mineral responses.

Records of the distribution of mineral deficiencies may themselves assist considerably toward the understanding of geomorphology and soil genesis. Certainly it seems that geomorphic history and geochemical considerations as much as soil profile morphology provide the key to our major and trace element deficiencies.

C. Soil Classification and Description

Over the last thirty years soil surveys and pedological work have led to the recognition of 45 great soil groups. These have been defined and classified most recently by Stephens (1956). These soil groups are listed below in Table IV arranged under their suborders (a–i) which although morphological by definition substantially reflect the gross moisture regime.

The soils with which this chapter is principally concerned are those found in the moderately humid parts of Australia or irrigated soils of drier areas to which fertilizers are applied. The other soils occur either in the restricted wet mountain zones or in the arid and semiarid areas where, with only minute exceptions, land use is on such an attenuated pastoral basis that fertilizers have found no place in the economy. Some soils are of such restricted occurrence (e.g. lateritic krasnozem), that no systematic knowledge of their fertilizer reaction is available.

The morphological and genetic features of the soils on which fertilizer response data are available are dealt with below. For convenience those soils with prominently related morphological characteristics are grouped together in some of the following classes:

1. Alluvial soils
2. Calcareous aeolian sands
3. Acid swamp soils
4. Podzols and ground-water podzols
5. Lateritic podzolic soils
6. Gray-brown, brown, red and yellow podzolic soils and meadow (gley) podzolic soils
7. Krasnozems
8. Lateritic red earths
9. Terra rossa
10. Black earths
11. Rendzinas and ground-water rendzinas
12. Fen soils
13. Solodized solonetz and solods
14. Solonized brown soils
15. Red-brown earths
16. Gray calcareous soils
17. Gray and brown soils of heavy texture

TABLE IV

Great Soil Groups of Australia Arranged Under Solum Classes and Suborders

I. Solum Undifferentiated

1. Alluvial soils: showing only sedimentary horizons
2. Skeletal soils: shallow stony soils with no significant profile development
3. Calcareous aeolian sands: with no significant profile development

II. Solum Differentiated

(a) Solum dominated by acid peat or peaty eluvial horizon

4. Moor peats
5. Alpine humus soils
6 Moor podzol peats
7. Acid swamp soils

(b) Solum acid and with organic, sesquioxide, and sometimes clay illuvial horizons

8. Podzols
9. Ground-Water podzols

(c) Solum acid and with clay and sesquioxide illuvial horizons

10. Lateritic podzolic soils
11. Gray brown podzolic soils
12. Brown podzolic soils
13. Red podzolic soils
14. Yellow podzolic soils
15. Meadow (gley) podzolic soils

(d) Solum acid to neutral and lacking pronounced eluviation of clays

16. Krasnozem
17. Lateritic krasnozem
18. Lateritic red earth
19. Terra rossa
20. Prairie soils

(e) Solum dark colored and slightly acid to neutral in eluvial horizons, calcareous illuvial horizons

21. Black earths
22. Wiesenboden
23. Brown forest soils
24. Rendzinas
25. Ground-water rendzinas
26. Fen soils

(f) Solum saline or showing post-saline structure in the illuvial horizon

27. Solonchak
28. Solonetz
29. Solodized solonetz
30. Solods
31. Solonized brown soils

(g) Solum with slightly acid to neutral eluvial horizons, and calcareous illuvial horizons

32. Red-brown earths
33. Brown earths
34. Brown soils of light texture
35. Calcareous red earth
36. Gray calcareous soils

(h) Solum with neutral to alkaline weakly developed eluvial horizons and calcareous and/or gypseous illuvial horizons

37. Gray soils of heavy texture
38. Brown soils of heavy texture

(i) Solum with deflated slightly acid to alkaline eluvial horizons and calcareous and/or gypseous illuvial horizons

39. Desert loams
40. Gray-brown and red calcareous desert soils
41. Red and brown hardpan soils
42. Desert sand plain soils
43. Calcareous lateritic soils
44. Stony desert tableland soils
45. Desert sandhills

1. Alluvial Soils

These soils, formed on juvenile alluvium with little profile differentiation except organic matter accumulation in the surface and sedimentary horizons vary a great deal in characteristics. They are, however, usually

among the more fertile soils of the areas in which they occur. Consequently, apart from superphosphate response there are only a few recorded responses to the fertilizer elements.

2. *Calcareous Aeolian Sands*

There is a broken but widely distributed occurrence of recent highly calcareous aeolian sand in the form of dunes along the southern Australian coastline. These dunes are most common in South Australia and on King and Flinders Island in Bass Strait. They are classified as aeolian sands of insignificant profile development; they are of very coarse texture and are extremely porous and overdrained. The only development consists of a darkening of the surface soil to a depth of several inches by organic matter and a slight concentration of lime with depth by secondary calcification. The organic matter confers a dark gray color on the soil and with the highly calcareous parent material may be considered to relate these soils to the rendzinas. They have some of the fertility problems of the rendzinas proper. These problems are in fact here accentuated to a remarkable degree. These soils where covered by pasture are used for sheep and cattle grazing with a high incidence of "coast disease." This is a fatal malady unless the stock are moved to other soils or given appropriate treatment with copper and cobalt. Zinc is marginal.

3. *Acid Swamp Soils*

In suitable localities of very restricted drainage in the more humid areas, especially of southern Australia, accumulations of acid peats occur. These have a scattered distribution but appear mostly to be associated with older coastal depressions. Where drainage is practicable, they are used with appropriate fertilizer programs for pasture production and potato growing. Western Australia produces most of its potatoes and a large part of its vegetable supply from such swamps. The peats vary greatly in depth, structure, and consistence, and degree of acidity. On draining, reaction values in the subsoils in exceptional cases may be as low at pH 2. They are commonly deficient in copper as well as phosphorus.

4. *Podzols and Ground-Water Podzols*

These soils have essentially the same morphology of the mineral profile as their counterpart in North America and Europe but the superficial and surface organic horizons have somewhat different degrees of development. This is due no doubt to the different biological associations, important features being the sclerophyll Eucalyptus forests and the Myrtaceous and Epacrid heaths associated with these soils.

In Australian podzols the superficial A_{00} horizon consists of a thin and variable scatter of leaves, twigs, and bark. The decomposed A_0 organic horizon is largely missing but invariably there is a pronounced accumulation of organic matter in the A_1 horizon, rendering it dark gray or speckled in color. The A_2 horizon is very variable in depth, ranging from a few inches up to several feet, and the color is light gray or nearly so. Textures in the A horizons are generally sand or sandy loam. The B_1 horizon consists of an accumulation of organic matter, or oxides of iron, or both, sometimes indurated. The B_2 horizon is variable in texture from sand to clay and is often somewhat mottled in color, with yellow and gray predominant. Parent materials and thus C horizons are variable in character and range from leached aeolian sands and coarse fluviatile deposits of highly siliceous materials to the more quartzitic sedimentary and crystalline rocks such as sandstones and granites.

In the ground water podzols the A_0 and particularly the A_{00} horizons are often more or less superficially present, depending on the nature of the associated vegetation. The A_1 horizon is generally coarse-textured and most frequently is more than 6 inches thick. The B_1 and B_2 horizons consist of more or less indurated accumulations of organic matter and iron compounds, occurring sometimes singly, sometimes together, and ranging from black to brown in color, and often referred to as "coffee rock." Below, the B horizon may continue as a mottled or gleyed layer of clay or a coarse-textured mineral horizon, passing gradually to the C horizon. The water table, an essential feature associated with these soils, is commonly found at a level in the profile below the B_1 horizon. Occasionally and sometimes seasonally, by saturation of the soil above the indurated pan, it rises to the surface. When the A_2 horizon is thus saturated it is noticeably stained by organic matter in solution. Parent materials are the same as for podzols. These soils are generally deficient in phosphorus and potassium. Responses to the trace elements copper and zinc are commonly obtained.

5. *Lateritic Podzolic Soils*

The soils of the Australian Pliocene land surface as judged by present-day remnants consisted of a very deeply weathered mantle in which laterite and silcrete occurred alone or together (Fig. 3). The former, a ferruginous and aluminous crust or carapace, occurred extensively in humid areas; and the latter, a dense secondary siliceous accumulation, in the drier areas; profiles containing both were found in the intermediate zone. Since the silcrete, although of great pedological interest, occurs in soils in present day arid or semiarid areas where fertilizers are not used, it is not considered further. In the southern more humid regions, the soils

which contain the laterite are today classified as lateritic podzolic soils. In the tropical and subtropical areas they are predominantly lateritic red earths, although the podzolic version also occurs.

The lateritic podzolic soils are largely the result of truncation by superficial erosion down to the laterite crust and redevelopment of the upper horizons of the soil profile thereon. There are, however, small areas where the original sandy A horizons are more or less intact as for example

FIG. 3. Many Australian soils especially the lateritic podzolic soils are impoverished because of very deep weathering and leaching. The photograph shows the great depth of light colored, almost white, kaolinitic material, the pallid zone, beneath the lateritic gravelly surface horizons and mottled zone of such a soil at Hoddy's Well in Western Australia.

in the Eleanor Sand on Kangaroo Island described by Northcote (1946). The common soil on the lateritic surface is a coarse-textured and very gravelly mass overlying the kaolinitic clay of the mottled and pallid zones of the old profile. On the beveled slopes occur soils reformed on the exposed mottled and pallid zones as well as on detritus from the eroding edge of the tableland. These soils are essentially podzolic and more or less contaminated with lateritic ironstone gravel. A correlation of the occurrence of the various sorts of lateritic podzolic soils with the topographical and horizon features of the sculptured Pliocene surface has been made by Stephens (1946) in a study of pedogenesis following the dissection of the lateritic regions of southern Australia.

The essential features of the lateritic podzolic soils are as follows:

There is a coarse-textured upper horizon of sand or sandy loam which contains nodular, pisolitic, vermicular, or massive laterite, making up sometimes as much as 80 per cent of the soil material. This horizon has a shallow accumulation of organic matter in the surface 2 or 3 inches and in the fine earth material of the remainder of the horizon. This remainder may be as much as 2 feet deep, is usually light gray or gray-brown in color and quite distinct from the dark brown ferruginous gravel with which it is mixed. The horizon beneath is a mottled clay or sandy clay of various colors, which rapidly becomes paler and coarsely mottled with red, red-brown, and yellow-brown splashes of color. This gradually gives way to a similar textured material with little or no mottling and a light gray or almost pure white color. This gradually merges into the parent rock which may be of almost any character. Usually the whole profile is several feet in depth, and sometimes the pallid zone and less often the mottled zone is virtually absent. The whole profile is acid in reaction. These soils are very deficient in phosphorus. Responses to copper, zinc, molybdenum, and less frequently manganese are widely but not universally obtained.

6. Gray-brown, Brown, Red and Yellow Podzolic Soils and Meadow (Gley) Podzolic Soils

This grouping of gray-brown, brown, red, and yellow podzolic soils and the hydromorphic meadow podzolic soils appears to have essentially the same components as in North America and as in some similar soils in Europe where however the nomenclature is both variable and different. As with the podzols and the lateritic podzolic soils, there are some conspicuous differences in the organic matter of the superficial and A_1 horizons of these soils compared to their counterparts elsewhere. The mineral profile morphology, however, bears a striking resemblance.

The light textured A horizons of the gray-brown podzolic soils follow the group name in color and are darkened in the A_1 by a distinct accumulation of organic matter. In the red and yellow podzolic soils, the A horizons vary from pale reddish-brown and light yellowish-brown to pale gray and again are darkened by organic matter in the A_1 horizon. The name of these groups follows more specifically the red and yellow B horizons. In the meadow podzolic soil the A horizon is variable in color from light gray to gray-brown. In these soils the A_1 is much darkened by organic matter and the A_2 is often flecked with rusty spots and contains small ferruginous concretions. In all the podzolic soils the A_2 horizons are separated from the B horizons by gradual to abrupt differentiations in texture. Thus, with the increasing depth of the profile, the minimal, medial, and maximal development of these soils are characterized.

The color and structure of the B horizons of the podzolic soils provide some of their most readily distinguished features. In the gray-brown podzolics the B horizon is brown to yellow-brown in color and of nutty to blocky structure; in the brown podzolics yellowish-brown to reddish-brown and nutty to blocky; in the red podzolics red to red-brown and friable granular to nutty, sometimes with aggregates forming larger structural units; in the yellow podzolics yellow to yellow-brown and granular to angular nutty; in the meadow podzolic soils mottled in color, yellow, gray, brown, and occasionally red, and coarsely structured and most often plastic. In all cases, C horizons are very variable and often show some flecking of color due to differential weathering of the minerals of the parent material. The parent materials encompass a wide range of rock types and transported materials.

The meadow podzolic soils commonly occur in low sites with restricted drainage, often where a permanent ground-water table rises into the solum in the wetter period of the year. However, they also occur on some slopes without a true ground-water table but with free water in the profile. Such free water frequently occurs on top of the B horizon and moves down slope during periods of profile saturation in the wetter months of the year. These soils generally have maximal profile development with a very sharp texture break between the A_2 and B horizons. Thus these soils almost certainly in their former minimal and medial stages of development belonged to the well-drained normal podzolic soils.

The podzolic soils occur throughout the moister parts of Australia. Red podzolics are less frequent in the cooler regions and more common in tropical areas. The gray-brown and brown podzolic soils are confined to southern Australia. As a broad group, the podzolic soils have been most extensively sown to pastures in the last twenty-five years. In southern Australia, they are the soils on which subterranean clover has responded severalfold to additions of superphosphate commonly supplemented with one or more of the trace elements. There are quite a number of recorded responses to sulfur. They are not commonly under permanent or even intermittent cultivation except in very restricted areas where deciduous fruits such as apples and pears and vegetables including potatoes are grown.

7. *Krasnozems*

Krasnozems, popularly referred to as red loams or volcanic soils and now known as latosols in the U.S.A., occur in the eastern Australian states from Tasmania to northern Queensland. There are very minor occurrences in South and Western Australia. They appear with increasing fre-

quency in northern and eastern tropical coastal and subcoastal areas and their relationships to various parent materials are quite complex. In humid areas of low to moderate temperatures such as Tasmania and Victoria, they occur only on highly weatherable ferruginous rock such as basalt. In humid tropical areas they rest on a wider range of parent materials, including some granites but excluding the most siliceous rocks. The weathering rate under tropical conditions appears to be fast enough to release sufficient hydrated ferric oxide from a variety of rocks to maintain soil flocculation and thus ensure the characteristic red color and granular condition of these soils.

In profile morphology, these soils are red, occasionally yellow-brown, deep, friable clay showing very little evidence of horizon development beyond the rather deep accumulation of organic matter in the surface soil. Although generally a clay in texture throughout the profile, the surface soil because of its organic matter and the flocculated nature of the clay has the tillage usually associated with a loam. The lower part of the profile, including the C horizon, is granular to nutty in structure and of a very friable and porous nature. Occasionally small ferruginous and manganiferous concretions are found in the profile.

Because of their favorable tillage and initial fertility compared to the podzolic soils among which they occur, these soils have always been favored for a wide range of cultivated crops as well as for sown pastures. In Queensland, a large portion of the sugar cane crop is grown on them and the growing of peanuts there is almost entirely restricted to them. In southern areas, they are favored for root crops, particularly potatoes, and oats and other cereal crops. Their high initial fertility has proved difficult to maintain but even so they are among the most productive of the arable soils of the more humid regions. They are variable in phosphorus content but generally not as low as the podzolic soils. They give small to moderate responses to superphosphate and increasing responses to potash with prolonged usage. The more acid soils often respond to molybdenum. Cobalt deficiency in animals is being recorded increasingly on them.

8. Lateritic Red Earths

These soils have the same geomorphic history as the lateritic podzolic soils (see 5. above). However, a similar correlation of soils and topographic features to that outlined for the lateritic podzolic soils has not yet been made for the lateritic red earths. In these soils there appears to have been a much greater preservation of the original red earth horizons above the laterite, steeper beveled dissection of the edges, and perhaps lesser development of soils *in situ* on the mottled and pallid zone materials. Some of the red earth horizons especially in the Brisbane area, where

they have been studied by Bryan (1938), show an incipient degree of podzolic soil development.

Lateritic red earths are red to light red soils with a deep profile containing an horizon of laterite with mottled and pallid horizons beneath. The A horizon is commonly sandy to loamy in texture and darkened with a little organic matter. It passes gradually into a finer-textured B horizon which is usually bright red in color and of a compact but vesicular structure. The horizon of laterite is of variable character as in the lateritic podzolic soils. The mottled and pallid zone horizons also appear to duplicate those of the lateritic podzolic soils. There is also a wide range of parent materials. Response to fertilizers is not well known but responses to molybdenum, boron, and iron as well as superphosphate have been recorded on them.

9. *Terra Rossa*

Highly calcareous parent materials, especially Tertiary marine limestones and Quaternary dune limestones, are common in the coastal regions of southern Australia. In the lower southeast province of South Australia and adjacent areas of Victoria, there is a maximum development of terra rossa and rendzina soils (see 11. below) on these formations, along with podzolic soils on leached sands. Minor occurrences of these soils also occur on these and older limestones in other areas. Although the simultaneous occurrence of rendzina and terra rossa is not universal, they are frequently found together. A study of this phenomena for these soils in South Australia has been made by Stace (1956), who shows the significance of the ratio of organic carbon to ferric oxide in the morphology of these soils.

Australian terra rossa range from reddish-brown to red in color, are generally shallow in depth, rarely exceeding 12 inches, and occur exclusively on limestone as parent material. They range in texture from sandy to clayey. In the lighter-textured terra rossa soils there is some diffuse textural horizon differentiation. In the clay-loam and clay soils, however, the profiles are characterized by a generally granular and nutty structure in the A and B horizons, respectively, rather than by horizons of textural contrast. Some profiles contain small amounts of ferruginous concretions. Terra rossa respond to superphosphate. Copper, zinc, and manganese have also given responses.

10. *Black Earths*

The black earths of Australia are confined to the eastern states where they range from southern Tasmania to east central Queensland. They occupy areas which are seasonally alternately wet and dry, in subhumid

to semiarid areas. In the south the winter period is moist, while in the north the wet season is in the summer. The parent material is variable and ranges from alluvium to predominantly non-siliceous rocks. Basalt, directly or indirectly as local alluvium, provides a significant part of the parent material of these soils.

These soils have been compared by some workers with the chernozem of Europe and North America, and by Hosking (1935) with the regur of India. They occur over a great range in latitude. To the south these soils are characterized by increasingly fine structure and higher organic matter content of the surface soil. Even in Tasmania, however, they hardly have the extremely well-developed structure and organic matter content of typical chernozem.

As expressed in Australia, black earths are deep profiles with dark colored surface and subsurface soils and with lime in the solum. They normally show some slight degree of textural horizon differentiation, the A horizon being black or nearly so, of clay-loam or clay texture, of granular to cloddy structure and up to 12 inches or more deep. The B horizon in its upper part is often almost as dark colored as the A horizon and is almost invariably a clay in texture. The B horizon changes gradually to yellow, brown, or yellowish-brown in color with depth, and is generally of rather coarser structure than the A horizon. Lime occurs as amorphous specks and powder, or pellets or concretions in the profile in the B horizon and invariably persists into the C horizon. The C horizon has quite variable characteristics. In some areas, profile contortions are widely developed and give a hummocky surface known as gilgai microrelief. This is commonly expressed as a well-marked pattern of "puffs" and hollows and occasionally as a parallel arrangement of elongated rises and hollows.

In contrast to black earths, prairie soils are not well developed in Australia. They have been observed in northern and southern coastal and sub-coastal New South Wales and in isolated instances in Victoria, Tasmania, and South Australia, but nowhere do they dominate what might be termed a soil region or province. Where they do occur they resemble the black earths except that they are generally of a finer structure in the A horizon, embrace a wider range of textures there, and show somewhat greater, but still not marked, texture contrast between the A and B horizons. They do not contain lime in the solum.

In areas of restricted drainage associated with black earth and prairie soils and to a lesser degree with podzolic and red-brown earth soils, there occur black, heavy-textured, seasonally waterlogged soils known as wiesenboden. Superficially they resemble black earths and generally contain

lime in the profile, but the dark colored surface horizons are deeper, more coarsely structured, and the subsoil is strongly mottled.

The black earths have a widely varying content of phosphorus up to as much as 0.5 per cent. Consequently, some of them, especially in Queensland and northern New South Wales, do not respond to superphosphate. Occasional responses to all the trace elements, especially zinc but excepting cobalt, have been recorded on them. Responses to sulfur have also been recorded.

11. Rendzinas and Ground-Water Rendzinas

The rendzinas are shallow, black to very dark gray, or dark brown soils resting on limestone. They are generally of medium to fine texture, lack significant development of A and B horizons, and have a pronounced structure varying from crumb and granular in the surface to angular nutty in the subsoil. Free lime is often present in the profile.

The rendzinas are sometimes associated with ground water which periodically invades the solum. These rendzinas are referred to as ground-water rendzinas to distinguish them from the drier soils. The effect of the water table is not particularly pronounced morphologically. There is some alteration in color of the lower part of the black soil to a drab yellow gray or gray. However, the water table at times inundates the surface and imposes a need for drainage before these soils can be properly utilized. These soils are particularly extensive in the lower southeast of South Australia where a national drainage scheme has reclaimed them for agriculture and intensive pasture production. They respond to superphosphate and to the trace elements zinc, copper, and manganese.

12. Fen Soils

In immediate coastal areas in South Australia and Tasmania, there occur limited tracts of alkaline to neutral fen peats. These are associated with younger coastal swales in areas of calcareous basement materials and alkaline telluric water. The peats are of variable depth and vary from well granulated to coarse fibrous types. The reaction of the profile is from neutral to alkaline. They are extremely fertile soils. The soils and vegetation of Eight Mile Creek Swamp, an example in South Australia, have been detailed by Stephens (1943) and Eardley (1943). These authors emphasize the similarity of these soils to the British fens.

As well as responding to superphosphate, these soils although highly fertile give quite large responses to copper, zinc, and manganese.

13. Solodized Solonetz and Solods

These soils, which occur more or less commonly throughout the subhumid and semiarid zones of Australia, in some localities assume dominance in a soil landscape. Notable examples of this are in the upper southeast of South Australia and in the southern part of Western Australia. Solonetz soils are relatively uncommon, while solodized solonetz both common and dominant in some areas. Solodic soils are often intermingled with and resemble some podzolic soils, so that they are difficult to separate with any confidence except on the basis of laboratory data.

The solonetz are characterized by the morphology of the B horizon which has the form of domed columns. These have approximate hexagonal cross section and vary from a square inch or two to over a square foot. The domes form the upper surface of the B horizon, and are sometimes practically hemispherical in shape. The A horizons vary in color from gray to brown and red-brown. When the profile is dry, a little of the A horizon material may be found in the cracks which open up in dry weather and separate the columns of the B horizon. There is usually a texture contrast between A and B horizons, and lime is found in the profile in the lower part of the B horizon. Parent materials are variable. Quite often some indications of salinity can be found on the landscape.

Solodized solonetz comprise solonetz soils which have suffered a further degree of leaching and profile differentiation, especially in the A horizon. This is expressed as a thin A_1 over a well-marked, light gray, distinctly bleached A_2 horizon which rests on top of the columnar and domed B horizon. The domes are sometimes altered to an oolitic form with a coating of light colored siliceous material on the upper surfaces and with some darkening of the sides of the columns below. Much material from the A_2 horizon is found in the cracks between the columns. Lime frequently occurs in the profile but often below the solum proper.

In the solodic soils the processes of leaching and alteration have been carried a step further. The light colored A_2 horizon remains as for the solodized solonetz but the B horizon is generally reduced to a roughly prismatic form with no conspicuous doming but with some staining of the prism faces. The color of the clay of the prisms is commonly gray-brown or slightly mottled. Lime is generally absent from the solum proper. As well as responding to superphosphate, these soils have also given wide responses to copper, zinc, and molybdenum.

14. Solonized Brown Soils

A special but widespread soil in southern Australia is the solonized brown soil. It is restricted to semiarid areas. It has been formed on highly

calcareous materials which form a mantle over much of the landscape which it occupies. For this and other reasons proposed by Crocker (1946), its calcareous parent material is considered, in part at least, to be of loessial origin. It occupies a landscape which has been wind sculptured into a fairly widely spaced dune formation, so that the soil as a group is bimodal there. Deep sandy soils occur on the dune and shallower generally finer textured soils occur in the interdune swales. The landscape was formerly covered by a Eucalyptus scrub called "mallee" and this name has long been used to refer to these soils and the regions of their occurrence. These regions, when cleared of the scrub, are devoted to wheat production and sheep raising. Rainfall ranges from 10 to 17 inches per year. Under irrigated conditions, tree and vine fruit production is common.

The lower situated subgroup consists of shallow gray-brown to red-brown sandy loam to loam soils, mostly less than one foot deep and lying over a deep accumulation of lime. In its upper part this lime has a strongly developed nodular or crustlike form, or both, and is more powdery but of finer texture with depth. The lime is accompanied by significant amounts of clay. Above the lime horizons there is a weak differentiation into A and B horizons.

The higher subgroup situated on the dunes consists of some feet of deep sandy soil yellow-brown to red-brown in color overlying an accumulation of lime. The lime is neither so abundant nor so nodular or crustlike as in the other subgroup and is accompanied by coarser soil until it gives way to highly calcareous clay at considerable depths. In the profile above the lime horizon, there is generally slight textural and color evidence of the development of a very weak B horizon.

In both subgroups profile morphology would rarely lead one to categorize these soils as solonized. However, a study of their chemical and physical characteristics by Prescott and Piper (1932) caused them to postulate that these soils have been subject to profound solonization because their exchange complex has a high proportion of sodium and magnesium and because the profiles are still notably saline at depth. A detailed study of the chemical and physical properties of an area of these soils at Coomealla in New South Wales has been made by Northcote (1951). Generally it may be inferred that the high proportion of lime in the subsoils precludes the usual physical effects of solonization. This is so despite a considerable degree of salinization followed by desalinization in the upper part of the profile. Under wheat cultivation these soils respond well to superphosphate. Where irrigated for horticultural purpose, responses to trace elements copper, zinc, manganese, and iron have also been recorded. Steely wool in sheep fleeces is controlled by the use of copper.

15. Red-Brown Earths

The red-brown earths (Fig. 4) which occur on a variety of parent materials are found most commonly in southeastern Australia but extend in a lesser degree to other parts of Australia where the climate is seasonal and subhumid. These soils are the mainstay of wheat production in south-

FIG. 4. The A and B horizons of the Belalie loam, a red-brown earth in South Australia showing the sharp definition of the boundary between the loam of the A and the prismatic clay of the B horizon. Such abrupt horizon definition, indicative of great maturity, is a very common feature of many Australian soils and always evokes comment from visiting pedologists.

eastern Australia. They are used in some areas of New South Wales and Victoria under irrigation for fruit and sown pasture production.

Profiles of red-brown earths are invariably clearly differentiated into A and B horizons. The A is one or more grades in texture coarser than the B horizon and generally but weakly crumb structured. The A horizon has

some accumulation of organic matter in the top four inches. The brown to red-brown A horizons overlay brighter and redder B horizons which exhibit clear nutty to prismatic structure. Lime occurs in the lower part of the B horizon and continues usually into the C horizon. The C horizon is composed of variable material and rests on a variety of parent materials, of which Pleistocene alluvium is the most common. The red-brown earths respond well to superphosphate. Responses to zinc and iron have also been recorded.

16. Gray Calcareous Soils

The gray calcareous soils of subhumid areas have shallow profiles gray or gray-brown in color in the surface soil of silty loam texture. The subsoils are similar in texture, darker in color and sometimes nearly black, granular in structure, and rest abruptly at shallow depth on limestone. These soils respond to superphosphate, zinc, and manganese.

17. Gray and Brown Soils of Heavy Texture

The gray and brown soils of heavy texture extend from the subhumid areas right into the desert areas. In desert areas, however, they are practically limited to fine-textured parent material in the alluvial flood plains of the intermittent streams which flow to the great central basin around Lake Eyre. Outside the arid area they are also commonly found on fine-textured alluvium but do extend to other very fine-textured parent materials. Their most intense use is for rice production under flood irrigation, producing over two tons of grain per acre. Rice production is, however, restricted. Normally they are used for pastoral grazing. Under the most favorable climatic conditions as in the Wimmera of Victoria they are successfully used for wheat production. Under irrigated conditions their infiltration rates are so low that no general success has attended attempts to grow sown pastures on them.

The gray and brown soils of heavy texture have simple largely undifferentiated texture profiles of brown or gray clays with little or slight A horizon development. Structure development is coarse or massive and under dry conditions the soil cracks widely in a subhexagonal pattern to a depth of several feet. Lime and gypsum frequently occur in the subsoil but one or both may be absent from the profile. Like the black earths, both soils are widely contorted by gilgai development. Under these circumstances, lime and/or gypsum may be present in the surface soils of the profiles on the mounds of these formations. These soils respond to superphosphate and there are occasional records of responses to zinc, copper, and iron.

D. A Soil Map of Australia

An amended soil map of Australia reconstructed from the earlier one by Prescott (1944) is presented here (Fig. 5). It is intended to show the distribution of the soils described above. Since some of the soils occur as

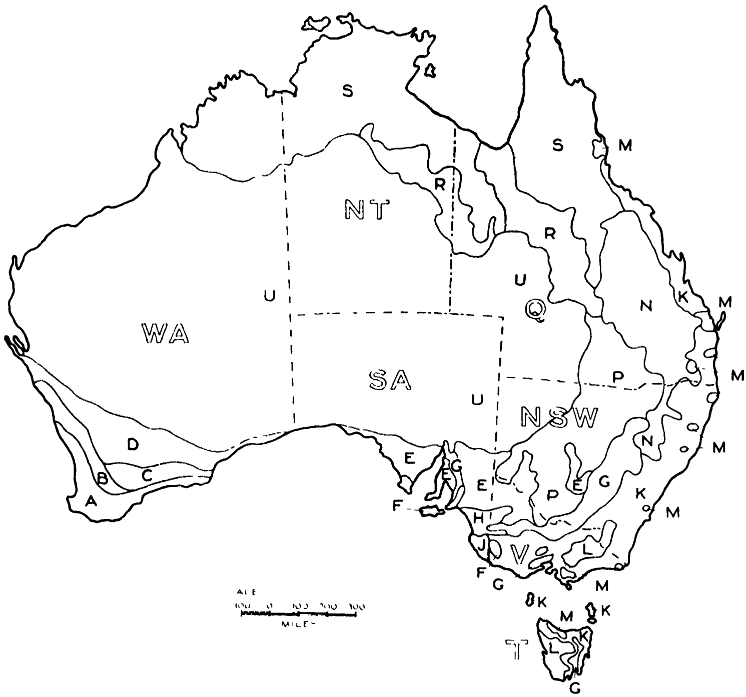

FIG. 5. A soil map of Australia showing regions composed of associations of great soil groups (see key).

immense tracts and others as quite minor geographic features it is necessary to depict them on the basis of associations of Great Soil Groups. Hence the legend of the map gives the approximate composition of each of the soil regions delineated in terms of predominant, minor, and small occurrences.

IV. The History of Fertilizer Use in Australia

Prior to 1890, practically no artificial fertilizers were used in Australia. Cereal crop production was mainly confined to soils of moderate natural

A Regional Soil Map of Australia
(Key to Fig. 5)

A. Predominantly lateritic podzolic soils with minor areas of podzols, ground-water podzols, acid swamp soils, brown podzolic soils and meadow podzolic soils and with very small occurrences of krasnozems, rendzinas, and terra rossa soils.

B. Predominantly lateritic podzolic soils and relic brown podzolic soils with minor areas of red-brown earths, and solonetzic soils.

C. Predominantly solodized solonetz, solonetz, and lateritic podzolic soils.

D. Predominantly solonized brown soils and lateritic podzolic soils with minor areas of red-brown earths, and calcareous lateritic soils.

E. Predominantly solonized brown soils with minor areas of solonetz, and solodized solonetz.

F. Predominantly lateritic podzolic soils and gray-brown, brown, red, and yellow podzolic soils with minor areas of meadow podzolic, solodized solonetz, solodic, terra rossa, rendzina, prairie, and acid swamp soils.

G. Predominantly red-brown earths with minor areas of gray and brown soils of heavy texture, gray calcareous soils, brown earths, and gray-brown podzolic soils.

H. Predominantly solodized solonetz with minor areas of solonchak, podzolic soils, terra rossa, rendzina, and calcareous sand with undifferentiated profile.

J. Predominantly ground-water rendzina, terra rossa, yellow podzolic soils, and meadow podzolic soils with minor areas of calcareous aeolian sands with undifferentiated profile, acid swamp soils. podzols, solodized solonetz, and solodic soils, and with very small occurrences of rendzinas, krasnozems, and fen peats.

K. Predominantly red and yellow podzolic soils with minor areas of skeletal soils, gray-brown and brown podzolic soils, meadow podzolic soils, solodic soils, podzols, and ground-water podzols, lateritic podzolic soils, lateritic red earths and very small occurrences of krasnozems, prairie soils, and undifferentiated alluvial soils.

L. Predominantly alpine humus soils, high moor peats, peaty podzols, and mountainous rock exposure with minor areas of podzolic soils in the mountain valleys.

M. Predominantly krasnozems with minor areas of lateritic krasnozems, and various podzolic soils.

N. Predominantly black earths with subdominant areas of lateritic podzolic soils and minor areas of podzolic soils, lateritic red earths, and red-brown earths.

P. Predominantly gray and brown soils of heavy texture with subdominant areas of brown soils of light texture, and minor areas of solonized brown soils and very small occurrences of red-brown earths.

R. Predominantly gray and brown soils of heavy texture with minor occurrences of lateritic podzolic soils, and lateritic red earths.

S. Predominantly lateritic podzolic soils, lateritic red earths, podzolic soils, undifferentiated alluvium and skeletal soils in the moister areas and skeletal soils, lateritic red earths, gray and brown soils of heavy texture, and brown soils of light texture in the drier areas.

U. Desert soil regions variously dominated by desert loams, red and brown hardpan soils, desert sandplain soils, stony desert tableland soils, desert sandhills, calcareous red earths, and gray-brown and red calcareous desert soils, with lesser areas of skeletal soils, gray and brown soils of heavy texture, calcareous lateritic soils, and solonchak.

fertility, such as the red-brown earths and the black earths. Stock raising was conducted on steppe, grassland, and savannah or on pastures developing on poor soils cleared from forest. Great areas lay undisturbed under scrub and forest vegetation. In wool producing areas the export of nutrients had not been great, but on cereal farms and in dairying areas the cumulative loss of nutrients, notably phosphorus and nitrogen, had certainly been considerable.

It is important to note that neither at that time nor at the present day is there any appreciable contribution to the Australian soil nutrient supply through the use of imported feedstuffs and farmyard manure. Livestock are not housed at any time of the year in Australia and for the most part, except in metropolitan milk supply areas, subsist on the pastures, good or bad. When feeding is adopted, the fodders are commonly home grown. Thus almost all nutrients exported from the farm and from the country have represented a net export, a marked contrast to northern Europe and parts of North America, with their heavy imports of fodders and the systematic use of farmyard manure.

The decline in wheat yields in the period 1860–1900 (12.8 bushels per acre in 1861–70 to 7.3 bushels in 1890–1900) was certainly due in considerable part to the depletion of initially low or moderate supplies of nitrogen and phosphorus in the soil. It is not surprising that when superphosphate was introduced as a fertilizer on cereal crops and when fallowing was adopted, each gave spectacular and highly profitable responses. Superphosphate was first used in Australia at Roseworthy Agricultural College, 30 miles from Adelaide, on a solonized brown soil in 17 inch rainfall country. The responses secured in South Australia and then in other states were so pronounced that superphosphate quickly became a standard fertilizer in almost all cereal areas. Its use also became general in horticulture, but did not extend to pastures until the early 1920's.

About this time Australian agriculture entered a new phase which has yet to reach its peak, so-called "pasture improvement," especially the use of pasture legumes. Up to this time Australia had depended for sown pastures on northern European species, plants such as *Lolium perenne*, *Dactylis glomerata*, and *Trifolium repens*. These were successful only in restricted climatically favored sectors of the southeast of the continent and even here only on the better soils. But about 1920, attention turned strongly toward a Mediterranean annual clover. The culture of this plant has been intimately involved in Australia's use of major and trace element fertilizers. These two developments have an inseparable history. This plant is *Trifolium subterraneum*, subterranean clover, ubiquitous in the Mediterranean basin, and first recognized as of potential pasture value by A. W. Howard, of Mount Barker, South Australia in 1899. The first commercial sale of seed,

a mere 30 lb., was not made till 1906 but the estimated area now sown is over 20 million acres. Howard used superphosphate on subterranean clover about 1905 but there are no early quantitative records of responses because experimenters at that time were unfamiliar with the measurement of pasture yields. Certainly no headway with this species was possible until it was fertilized with superphosphate. This practice is now so general that the phrase "sub and super" has become a farming idiom across southern Australia.

Subterranean clover with its excellent adaption to the Mediterranean and uniform rainfall areas became at once a boon and a challenge. At first in South Australia and then in Victoria, Western Australia, Tasmania, and New South Wales it opened a completely new phase in the country's agriculture. New varieties, found occurring naturally as accidental introductions, greatly extended the climatic range of the original Mount Barker variety of South Australia. The early flowering variety DWALGANUP, able to set its seed within a short growing season, was found in the southwest of Western Australia. Commercialization of this variety increased the zone over which the species could be grown in that state by an estimated 25,000 square miles. "Sub and super" provided a combination which met the well-nigh ubiquitous deficiencies of both phosphorus and nitrogen. The use of superphosphate extended also to more favored areas using white clover (*Trifolium repens*) as the pasture legume. Barrel medic (*Medicago tribuloides*) has become of similar importance for pastures in many cereal rotations, particularly on soils of high pH. North of latitude 28° S in the subtropical and tropical regions of Queensland, no legume has yet achieved wide success and fertilizer use on pastures in these regions is still very limited.

The development of the use of pasture legumes and superphosphate was checked by the economic depression of the 1930's and by the acute shortage of superphosphate (1.1 million tons in 1939 to 0.48 million tons in 1943) during the war years when the Japanese captured Nauru Island, a Pacific deposit of rock phosphate supplying most of our needs. In the postwar period, despite a temporary inability of fertilizer factories to meet the rising demand, the consumption of superphosphate has risen from 773,400 tons in 1945 to 1,800,000 tons (estimated) in 1956–1957. Whereas in 1939 32 per cent of the total was used on pastures and 68 per cent on crops, by 1956 some 60 per cent of the greatly increased consumption was used for the top-dressing of pastures. Gruen postulated (1955) that current trends indicated a probable doubling of consumption in the ensuing 10 years, principally due to the development of new areas to "improved" pasture but also due to heavier rates of application. To date, this forecast has been sustained for the Commonwealth.

In 1928 the first Australian record of a trace element deficiency was made at the Waite Institute in South Australia, when manganese was used to control "gray speck" of oats on a rendzina soil. Since that time copper, zinc, molybdenum, boron, and iron deficiencies have been recorded. Some of these deficiencies have been found on a great diversity of crops and soils and over very extensive areas. In particular the use of copper, zinc or molybdenum, or combinations of these elements, has enabled the growth of pasture legumes where previously little or no success had been gained by the use of superphosphate alone. Responses by crops and horticultural plants have also been of great economic importance, but the use of trace elements on pasture legumes has had a distinct and critical function. This has been to raise the nitrogen status of vast areas of soils of extremely low natural fertility. Commonly the trace elements have not been merely remedial treatments for indifferent pasture growth; in most instances they have enabled legume growth where without them no pasture establishment was possible. It is not stating too strong a case to describe the use of fertilizers on pasture legumes on acutely infertile soils in southern Australia as a vast reclamation scheme. This achievement is as significant, though not as difficult, as reclaiming lands from the sea.

Copper and cobalt deficiencies of livestock have also proved to be widespread. Commonly they have remedied serious ailments; in some instances they have proved necessary for reproduction and even for survival.

No census data are available for the use of trace elements throughout Australia, but Table V gives a list of superphosphate-trace element fertilizer mixtures sold in the state of South Australia in 1956–57. This table illustrates the importance of these nutrients.

Ten per cent of all the superphosphate was sold with one or more added trace elements and was sufficient to fertilize over 500,000 acres. When it is realized that copper, zinc, and molybdenum, the principal trace elements used on pastures, apparently do not require reapplication in less than five years or so, it will be appreciated that the area to which trace elements have been applied may well exceed one third of the total area fertilized in South Australia.

Two decades of predominant interest in trace elements preceded 1950. Since 1950, interest in trace elements has been supplemented by renewed interest in the major elements. Phosphorus is being more fully examined. It has also been shown that the use of superphosphate (containing gypsum) to correct phosphorus deficiency has concealed deficiencies of sulfur. Potassium, though long used for sugar and horticultural crops, is increasingly used for pasture production over extensive areas. Lime is being more fully investigated. Though new areas of trace element deficiency are being con-

TABLE V

Superphosphate-Trace Element Fertilizer Mixtures Sold in the State of South Australia 1956/57

Mixture	Tons
Super + Cu	6,551
Super + Mo	5,817
Super + Co	1,957
Super + Zn	1,596
Super + Mn	1,238
Super + Cu + Zn	16,316
Super + Cu + Mo	1,171
Super + Cu + Co	570
Super + Cu + Zn + Mo	1,176
Super + Cu + Co + Zn	195
Other trace element mixtures	3,436
Total superphosphate + trace element mixtures	approx. 40,000 tons
Super without trace elements	approx. 380,000 tons

stantly identified, the several major elements are assuming a new importance in our fertilizer economy. Superphosphate still dominates the scene, but potassic and nitrogenous fertilizers, lime, and gypsum are showing a steady upward trend from the present low levels of consumption.

V. Phosphorus and Nitrogen Deficiencies

A. The Phosphorus and Nitrogen Status of Australian Soils

The dual deficiency of phosphorus and nitrogen in nearly all soils has been a basic factor influencing the pattern of Australian agriculture (Fig. 6). Values for phosphorus in surface soils range from virtually trace amounts, less than 0.0001 per cent phosphorus, to isolated figures of 0.5 per cent with a great preponderance of values below 0.03 per cent. Nitrogen which shows the usual correlation with rainfall (Prescott, 1931) also varies widely, generally being between 0.01–0.05 per cent in the drier regions, and with values from 0.03 per cent upward in moister areas. Where rainfall is as high as 150 inches per year nitrogen may reach 0.8 per cent, and in swamps and fens, as much as 2 per cent.

The variation in the content of these two elements in surface soils of the important great soil groups is indicated by the following data. For sandy podzolic soils on which plantations of *Pinus* species have been attempted in Western Australia, Kessell and Stoate (1938) record values for

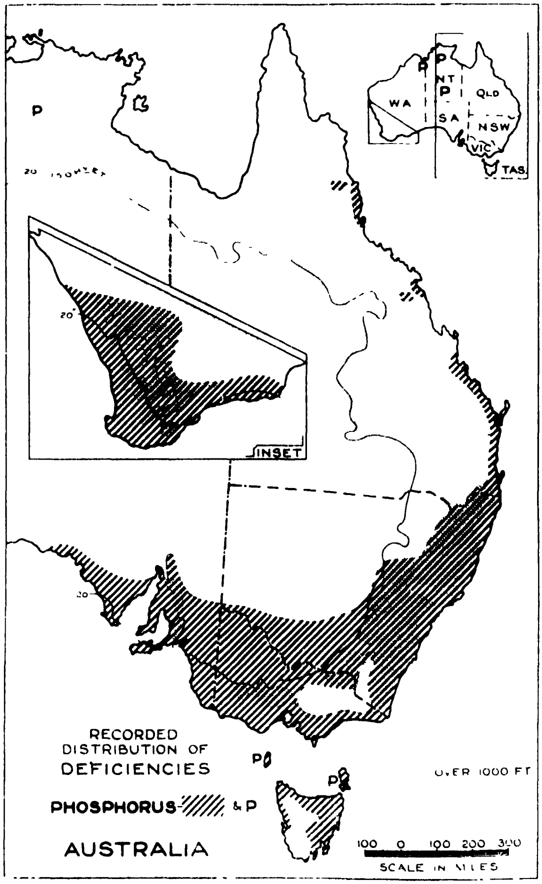

FIG. 6. Recorded distribution of phosphorus deficiency in Australia. Widespread phosphorus deficiency in cattle is not shown.

total phosphorus of less than 0.0001 per cent and nitrogen occasionally down to 0.02 per cent. On solodized solonetz and solodic soils in the upper southeast of South Australia, Taylor (1933) records figures for phosphorus of 0.002 per cent and for nitrogen around 0.03 per cent. Slightly higher figures have been widely recorded on podzols, podzolic soils and lateritic podzols in all states, with phosphorus rarely exceeding 0.01 per cent and nitrogen being more variable and sometimes reaching 0.2 per cent. On the solonized brown soils which are widely used for cereal growing, phosphorus has a modal value of 0.006 per cent and nitrogen of 0.04 per cent.

The red-brown earths which are more productive but respond moderately strongly to superphosphate have modal values of 0.02 per cent phosphorus and 0.09 per cent nitrogen. Rather conspicuous for their higher values are the widespread black earths of eastern Australia with values for phosphorus commonly ranging from 0.03 to 0.5 per cent and for nitrogen from 0.1 to 0.6 per cent. In the restricted but important agricultural areas of the krasnozems the corresponding figures are for phosphorus, 0.02 to 0.35 per cent and for nitrogen 0.1 to 0.8 per cent. Each of these latter soils is quite widely but not exclusively associated with basalt or its alluvial derivatives. Basalt seems to be one of the few rocks in Australia comparatively rich in phosphorus. Some of the black earths do not respond to additions of superphosphate; the kraznozems usually do but to a much lesser degree than the podzolic and other soils lower in phosphorus.

B. The Use of Phosphatic Fertilizers

Phosphorus deficiency has been met by the use of superphosphate to the exclusion of all other phosphatic fertilizers (Fig. 7). Reference has

Fig. 7. Extreme phosphorus deficiency on a lateritic podzolic soil on Kangaroo Island, South Australia. Pasture sown to subterranean clover photographed in its fourth year. Left of figure: no phosphorus. Right of figure: plots receiving superphosphate annually.

already been made to the first use of this fertilizer on cereal crops in South Australia. Table VI shows how greatly phosphorus contributed to increased cereal production at the turn of the century.

TABLE VI

Effect of Phosphorus on Cereal Production, ca. 1900

Soil and Location	Wheat, bushels per acre		Rate of super per acre
	Nil	Super	Lbs.
South Australia (Anonymous, 1897–1898)			
Presumably solonized solonetz, Murray Bridge	3	12	224
Presumably solonized solonetz, Tatiara	6	15	112
Presumably solonized brown soil, Nantawarra	5.5	13	90
Presumably solonized brown soil, Maitland	3	8	?
Victoria (Howell, 1902)			
Presumably mainly podzolic soils, Bendigo-Marlborough (mean of 7 farms)	12.7	17.4	51
Presumably mainly solonized brown soils, Boort-Wycheproof-Charlton (mean of 11 farms)	5.9	9.0	51
Presumably mainly red-brown earths, Elmore-Echuca (mean of 4 farms)	10.7	16.3	51
Presumably mainly gray and brown soils of heavy texture, Lillimur-Nhill (mean of 18 fields)	7.9	11.2	51
New South Wales (Guthrie and Helms, 1901)			
Presumably red-brown earth, Wagga	7.7	13.3	300

The value of superphosphate application to cereals tended to be established in terms of the "optimum dressing" for various districts in the same sense that other experiments of this period determined "optimum seed rates." Farmers were advised to adopt a ½ or ¾ cwt. (one hundredweight = 112 lb.) dressing with their wheat, according to district, and this advice became engrained and static. For forty years little thought was given to the possible cumulative effects of phosphorus application to wheat crops, despite the fact that a 20 bushel crop was removing only about 35 per cent of a ¾ cwt. dressing. Woodroffe and Williams (1953) made an investigation of the value of residual phosphorus on a red-brown earth, the Urrbrae loam, at the Waite Institute. It was shown that on fields to which there had been previous applications totaling 19 cwt. of superphosphate, there was no response to a current dressing.

A typical profile of the phosphorus-deficient[1] Urrbrae loam has the

[1] The profiles of many of the soils referred to in this section as suffering phosphorus deficiency are not here described in detail, but are referred to more fully under the sections on other deficiencies. Appendix A provides a complete list of the profile descriptions given throughout this article.

following features. The A_1 horizon, 0–7 inches, consists of a brown fine sandy to silty loam of weak crumb structure, pH 5.7, phosphorus = 0.02 per cent, nitrogen = 0.11 per cent; the A_2 horizon, 7–13 inches, of compact brown loam, pH 5.9; the B_1 horizon, 13–30 inches, of red-brown clay of friable prismatic structure, pH 6.6; the B_2 horizon, 30–35 inches, of dark red-brown clay of similar structure, pH 7.2; the B_2C horizon, 35–45 inches, of brown to red-brown clay of crumbly irregular structure containing 9.9 per cent $CaCO_3$, pH 8.6; and the B_3C horizon, 45–69 inches, a similar clay, with 2.4 per cent $CaCO_3$, pH 8.5.

Sims (1956) similarly showed the cumulative residual effect of phosphorus on gray soil of heavy texture at Longerenong Agricultural College. A 24 per cent response was given to 1 cwt. of superphosphate in the period 1912–1916; the response to the same dressing in the period 1947–1950 was only 6 per cent. Approximately 16 cwt. superphosphate had been applied in the intervening 35 years.

These findings have led to a revision of outlook toward the use of phosphorus on cereals. Although there are many districts in which phosphorus responses are still very profitable, there is a recognition that previous applications have strong residual values. In South Australia, the empirical advice now given to wheat growers is that if the total dressing in hundredweights applied during the history of the field exceeds one half of the annual rainfall (a winter rainfall, mainly falling during the growing of the crop) in inches, then the curtailment of dressings may prove possible. Clearly this relationship will differ greatly according to soil type, and much more information is needed on these residual effects. Meanwhile superphosphate is still used on virtually all those cereal crops which are sown on fallow or on land prepared from clover ley. With either preparation, the phosphorus response is not seriously limited by the deficiency of available nitrogen. However, in the case of "stubble crops" (i.e. the second consecutive cereal crop), which are commonly oats or barley, superphosphate may give little response because of nitrogen limitation and is commonly omitted. This differing interaction of phosphorus and nitrogen on fallow and stubble was shown in early work in the climatically favorable cereal environment of the Waite Institute. It emphasized the intensity of both deficiencies on unfallowed soil. (Table VII).

Phosphorus is used on almost all field and horticultural crops throughout the Commonwealth and is usually indispensable for satisfactory plant growth. The major exception is the growing of crops on the black earths of northern New South Wales and of Queensland. Here, as already noted, phosphorus levels are relatively high and field experience has shown no response to superphosphate unless there is a deficiency of sulfur.

In the tropical north, phosphorus responses by crops have been re-

TABLE VII

Differing Interaction of Phosphorus and Nitrogen on Fallow and Stubble

	Increase in wheat yields, bushels per acre, 1931–1934	
	On long cultivated fallow	On stubble (i.e. following wheat in the previous year)
P (2 cwt. super)	22.5	3.2
N (1 cwt. sulfate of ammonia)	5.9	5.6
$P_s + N$	22.9	11 4

corded at Katherine, Northern Territory, on lateritic red earths, at Alice Springs, Northern Territory, on calcareous red earths and at the Ord River in the northwest of Western Australia on gray and brown soils of heavy texture. So far this latter soil has shown no response to any other element, major or minor. The following profile by Burvill (1945) describes the Cununurra clay at the Ord River on which irrigated rice yields were increased from 746 lb. per acre to 1990 lb. per acre with 2 cwt. of superphosphate per acre. The surface soil consists of about 4 inches of dark gray-brown crumbly and cloddy clay, pH 7.5, nitrogen = 0.04 per cent, and phosphorus = 0.008 per cent. This overlies a considerable depth of tough, dark gray-brown clay with small nodules of lime and small soft black concretions. This clay becomes more friable with depth and lime nodules increase in size. At about 7 feet is found a brown friable micaceous fine sandy clay with lime nodules.

The first use of superphosphate on pastures in the early 1920's was in areas carrying perennial native pastures (mainly of *Danthonia, Stipa,* and *Chloris* spp.) in which subterranean clover was introduced by surface broadcasting or by "scratching" without full cultivation. Use in these areas continues, but there has also been a major extension of the use of phosphorus by its application to extremely poor soils (e.g., phosphorus < 0.01 per cent, nitrogen < 0.05 per cent) which previously carried forest, worthless scrub, or heath. Here the responses have been spectacular, often with a complete failure of establishment in the absence of superphosphate; in some instances trace elements are needed, in others only phosphorus. Table VIII shows the magnitude of responses on several soil groups by sown pastures wholly or largely composed of clovers.

A profile typical of many of the podzolic soils on which great increases in production have been achieved by the use of superphosphate on le-

TABLE VIII

Response to Phosphorus by Sown Pastures Wholly or Largely Composed of Clovers

Soil group	Cwt. of dry matter −P	Cwt. of dry matter +P	Rate of super (lb./acre)	Other deficiencies excluding N
Podzolic soil (Trumble and Donald, 1938)	4.3	27.0	224	-
Podzolic soil (Carter et al., 1956)	1 2	22 5	224	K?
Gray-brown podzolic (Anderson and McLachlan, 1951)	45	62	148	S, Mo
Gray-brown podzolic (Anderson and McLachlan, 1951)	13	37	448	S, Mo
Lateritic podzolic (Rossiter and Ozanne, 1955)	2.5	41	224	S, Zn
Low humic gley (meadow podzolic) (Andrew and Bryan, 1955)	Failed	11 3	672	Ca, K, Cu, Zn, Mo, B
Krasnozem (Crofts et al, 1955)	23 4	52 4	148	K, Mo, Cu?, Zn?

guminous pasture, in this case without trace elements, is that of the Kalangadoo sand, a meadow (gley) podzolic soil. The A_1 horizon consists of up to 12 inches of gray loamy sand with a moderate content of finely divided organic matter, pH 5.7, nitrogen = 0.102 per cent, phosphorus = 0.008 per cent; the A_2 horizon of about 12 inches of light gray sand with prominent pink sand grains and a little ferruginous concretionary gravel; and the BC horizon of up to 9 feet of mottled, yellow gray and brown, somewhat coarsely structured clay with abundant red inclusions. The parent material is Pleistocene alluvium overlying Miocene limestone at depth.

Carrying capacity of farms on this soil has been raised from less than 1 sheep per acre on natural Danthonia pasture to as much as 5 sheep per acre on sown pastures based on subterranean clover and receiving annual applications of superphosphate. In a slightly drier area at Kybyolite, sown pastures on a very similar soil under strictly controlled experimental conditions have developed a carrying capacity of 4.5 sheep per acre.

Evidence of strong residual effects of phosphorus applied to pastures has been gained in many areas. Though some soils exhibit low availability of applied phosphorus they still show a substantial effect of previous dressings. Table IX illustrates the recovery of phosphorus in successive years on plots grazed by sheep.

Results of this kind have led to the viewpoint that the top-dressing of pastures, especially of sheep pastures from which the export of phosphorus

TABLE IX

Recovery of Phosphorus in Successive Years on Plots Grazed by Sheep

	First year dressing (cwt)	Per cent recovery of first year dressing: First year	Second year	Third year
Trumble and Donald, 1938	2	20 8	15 5	13 7
Podzolic soil	4	19.6	16 6	14 5
Rossiter and Ozanne, 1955	1	28	11	
Lateritic podzolic soil	4	25	17	
	8	18	15	

is low, can be regarded on many soils as a continuous building of the level of available phosphorus, a "bank" closely proportional to the total of the previous dressings applied.

This viewpoint is supported by the results of a farm survey of 44 fields (Donald and Williams, 1954) in which subterranean clover and superphosphate had been used on a gray-brown podzolic sandy loam on granodiorite on the southern tablelands of New South Wales. Some of the fields carried untreated, native pasture, while others had received superphosphate at a mean annual rate of ½ cwt. per acre for varying periods up to 25 years. A comparison of seven untreated soils with seven respectively contiguous soils, which had received an average dressing of 9 cwt. of superphosphate in previous years, showed a current phosphorus response of 54 per cent on the virgin soils and only 13 per cent on the treated soils. The survey indicated that a cumulative application of ¾–1 ton of superphosphate would give a full correction of phosphorus deficiency on these soils and that this may be of quasi-permanent duration, requiring only small maintenance applications to sustain production.

The findings on the residual value of phosphorus applied to pastures are incorporated in current advice to graziers: first, that they should make generous applications in the early years of establishment of leguminous pastures to build up the available phosphorus as rapidly as possible, and secondly, that applications may be made every second or third year (at a correspondingly higher rate) instead of annually in order to reduce the costs of application. This latter aspect was specifically investigated at several sites on podzolic soils of the southern tablelands of New South Wales and it was shown that on these soils (Anderson and McLachlan, 1951) quadruple applications each fourth year were of comparable value to annual dressings.

The concept of progressively building the status of available phos-

phorus, as contrasted to the former approach of a dressing to meet the needs of a current crop, is leading to the realization that there are now individual fields or properties in which no response to further phosphorus application can be expected. On such properties, certainly still very few in number, the continued use of superphosphate at previous rates is wasteful. Work is in progress to attempt to define chemical and agronomic criteria for the recognition of this critical level.

The fate of the applied phosphorus on very poor soils which are being built in fertility by the use of superphosphate and pasture legumes, is of considerable interest. Australian and overseas work have shown that the phosphorus is retained in the top few inches of soil. Furthermore, in the survey referred to above (Donald and Williams, 1954) it was found that on a podzolic soil, initially of low organic matter status, the added phosphorus was comprised of about 50 per cent organic phosphorus of low availability and about 50 per cent readily acid- or alkali-extractable inorganic phosphorus, irrespective of the number of years over which it had been applied. The growth of plants was dependent on this latter fraction and thus on the total past application of fertilizer.

It was also found that as the organic matter rose under the influence of clover growth, it maintained a constant ratio of C : N : S : P (Williams and Donald, 1957). On these soils this ratio was 155 : 10 : 1.4 : 0.7, both in the native organic matter and the incremental organic matter. Thus the building of the fertility of these soils involves *ipso facto* the tying up of a part both of the phosphorus and sulphur of superphosphate in the incremental organic matter. The quantity of phosphorus entering the organic matter will be considerable as soils are converted from extremely low to moderate or high fertility; on the other hand cultivation leading to oxidation of organic matter would no doubt release phosphorus to available form as it does in the case of nitrogen.

C. The Use of Nitrogenous Fertilizers

The problem of the almost ubiquitous deficiency of nitrogen on Australian soils has been met in several ways. Nitrogen declined, together with phosphorus, under the continuous cultivation on the cereal soils. The decline in productivity was not fully recognized as involving a growing nitrogen deficiency. When the long bare fallow was adopted in rotation with the cereal crop in the 1880's, the value of water storage in the fallow was commonly acclaimed as the factor giving greatly increased yields. Water storage is of course important in dry areas or drier seasons, but the incubation of available nitrogen in the fallow is often of greater significance. Here then was a practice permitting a more ruthless exploitation of the soil fertility and the maintenance and improvement of yields. Continuous

cultivation, both in the cereal year and in the maintenance of the alternating "clean fallow" was disastrous also in its effects on structure. Water erosion became a serious problem in wheat districts. More recently the use of short-term leguminous pastures has become the basic approach to fertility maintenance in cereal districts. In many areas the long bare fallow is being dropped from the rotation. Wheat yields show a marked upward trend.

Meanwhile, from 1930 on, sown legumes were being used for pasture development on poor soils. Many of these have a virgin nitrogen content as low as 0.02–0.05 per cent. When subterranean clover was first used, the emphasis was on its value as fodder, but within a decade it was realized that soils on which it was flourishing were being transformed in their fertility. This function of pasture legumes now ranks equally in the landholder's mind with that of the provision of feed. Cook (1939) measured the changes in total nitrogen on a meadow podzolic soil at Kybybolite, South Australia and found the differences recorded below:

	Soil N under two pastures lb./acre of N	
	0–2 inches	0–6 inches
Natural pasture with no fertilizer	340	642
Sub clover with 90 lb super per year for 14 years	1,013	1,746

This was a gain of 36 lb. nitrogen per acre per year or of 83 lb. per cwt. of superphosphate used. In another survey Donald and Williams (1954) also found an increment of about 85 lb. of soil nitrogen in the top 4 inches, per cwt. of superphosphate used. Even where the nitrogen content had been increased from 0.05 to 0.15 per cent it continued to rise in linear manner with superphosphate application (Section VI, B.). It is doubtful if any of the "improved soils" in southern Australia have yet reached a nitrogen level in equilibrium with the altered environment and there is as yet little indication of what this value might be under the higher status of carbon, phosphorus, sulfur, and calcium achieved by the use of superphosphate.

It is notable too that the cation exchange capacity is affected by the increasing level of organic matter, or, less probably, by the upward carriage of nutrients by more vigorous and deeper rooted plants. Williams and Donald (1957) found that each cwt. of superphosphate had given an increase of 6.5 lb. exchangeable potassium, 5.2 lb. exchangeable magnesium, and 25.5 lb. (exceeding the applied calcium) exchangeable calcium.

Concurrently the increase in exchangeable hydrogen led to a fall in pH of 0.06 units per cwt. of applied superphosphate, an effect which may yet involve secondary problems of nutrient availability.

Australia has pinned her faith to pasture legumes as the means of improving the nitrogen status of the soil and the nitrogen nutrition of non-legumes. In contrast to most other countries using substantial amounts of fertilizers, Australia has an almost insignificant use of fertilizer nitrogen as shown by the data for annual consumption in Table X.

TABLE X

Annual Fertilizer Nitrogen Consumption in Australia

Year	Sulfate of ammonia (tons)	Nitrate of soda (tons)	Urea (tons)
1919	158	—[a]	—
1929	16,061	[a]	
1939	57,835	—[a]	—
1949	66,801	—[a]	—
1952	74,417	808	[a]
1956	94,535	1,974	1,000

[a] Not available

Though consumption is increasing, it is still almost entirely used on fruit and vegetable crops and on sugar cane; none is used on pastures, very little on cereals. Table XI gives a breakdown of fertilizer nitrogen use in Australia.

TABLE XI

Uses of Fertilizer Nitrogen in Australia

Crop.	Per cent consumption of nitrogen fertilizers
Sugar cane	50
Citrus	14
Other fruit	15
Vegetables (truck crops)	14
Potatoes	5
Miscellaneous	2

This position is explicable on several grounds. First the cost of nitrogen in Australia is high; in 1957, 100 lb. of nitrogen had the same value as

730 lb. of wheat; secondly, the cheap and effective addition of atmospheric nitrogen by legumes is undoubtedly the best economic approach to the conversion of poor soils and this has tended to obscure the potential role of fertilizer nitrogen; and thirdly there has been a prejudice against the use of nitrogenous fertilizers as giving a leafy, succulent growth, liable to drought damage.

It is now appreciated that within the framework of a soundly based rotation, which includes leguminous pastures, fertilizer nitrogen may have a useful role. Work is being resumed in this field. There is a growing appreciation that pasture legumes may not meet all needs for nitrogen. This is so because of the inadequacy of their yield in some environments (e.g. very hot, irrigated areas and subtropical regions still lacking suitable legumes). Also, even when legumes have substantially raised the nitrogen level, the readily available nitrogen may still be low at particular times of the year or immediately following the cultivation of leys. These are aspects currently under study. Meanwhile the prejudice against fertilizer nitrogen slowly fades; there is the prospect of its increasing use in Australia, although for many years to come it will be a minor contributor compared to by pasture legumes.

VI. Deficiencies of Other Major Elements

A. Potassium Deficiency

The small but rapidly increasing use of potassic fertilizers is shown by the data in Table XII.

TABLE XII

Potassic Fertilizer Consumption in Australia

Year	Tons K_2O
1935–1939 (Mean annual)	5,787
1946–1949 (Mean annual)	6,291
1952	9,592
1956	19,031

The doubling of consumption in recent years has been due not only to increased rates of application to sugar cane, fruit, and vegetable crops, but more particularly to the recognition of widespread potassium deficiency of pastures especially in southern Victoria and in Tasmania. These changes in use are illustrated by the figures for 1952 and 1956 in Table XIII.

TABLE XIII

Uses of Potassic Fertilizer in Australia

Crop.	Tons of K fertilizer	
	1952	1956
Fruits	5,117	8,121
Potatoes and vegetables	3,125	5,689
Sugar cane	7,341	11,075
Tobacco	326	569
Pastures	196	5,516
Other crops	78	704
	16,183	31,674

Sugar cane, fruits, vegetables, and potatoes are principally grown in high rainfall areas on podzolic soils, krasnozems, and alluvial soils. The soils of the sugar cane areas of coastal Queensland are located in areas of high rainfall (up to 160 inches per year); the heavy leaching and the gross demand for potassium by cane crops make this fertilizer indispensable for maximum production.

An example of a weakly lateritic krasnozem profile on basalt from the very high rainfall area ($>$ 100 inches per year) near Innisfail in North Queensland, as described by Teakle (1950), has a red-brown porous friable clay surface soil with a reaction of pH 5.6, phosphorus = 0.09 per cent, nitrogen = 0.17 per cent, and in a total exchange capacity of 17.4 m.e. per cent it has 2.4 m.e. per cent exchangeable metal ions of which potassium is 0.15 m.e. per cent. In the subsoil the corresponding figures are total exchange capacity 12.4 m.e. per cent, total metal ions 0.53 m.e. per cent, and potassium 0.14 m.e. per cent. The whole profile, which is many feet deep, consists of friable red clay with some lateritic segregations at depth along with some white mottling.

The first record in Australia of the response of pastures to potassic fertilizers was in Victoria in 1932 (Report of Victorian Pasture Improvement League, 1933). Some of the deficiencies are induced, especially by heavy cropping or the cutting of hay, but they also occur on virgin podzolic soils. Clover growth especially is adversely affected. In fertilizer trials on pasture at 21 sites in eastern Victoria all centers showed both phosphorus and potassium response, while 4 also showed copper response, 18 showed molybdenum response, and 8 showed a response to lime (Drake and Kehoe, 1956). The following potassium–molybdenum interaction on an acid sandy podzolic soil near Bairnsdale illustrates such a dual deficiency, occurring where phosphorus is also lacking:

	Lb. of pasture per plot (P basal)	
	−K	+K
−Mo	15.8	25.4
+Mo	17.3	38.7

Residual effects of a dressing of 1 cwt. of potash salts per acre are considerable under grazing conditions, and may extend for as long as 4 to 5 years. Because all potassic fertilizers are imported from Europe and are of high cost this is an aspect of great economic importance.

Similar responses to potassium have recently been obtained on a long used soil, the Frodsley sandy loam, described by Loveday (1953) in Tasmania. Until recently, pasture and animal production on this soil were satisfactory with the use of superphosphate only. Potassium deficiency has again apparently been induced by hay making.

A typical profile of this soil consists of gray-brown sandy loam about 6 inches deep, pH 5.5, nitrogen = 0.225 per cent, phosphorus = 0.016 per cent, and exchangeable potassium 0.16 m.e. per cent, with some considerable variation in this figure from profile to profile. The subsurface consists of light gray-brown loamy sand with some ferruginous concretions and this sharply overlies a much mottled clay subsoil of some depth. The parent material is alluvium of a Pleistocene river valley terrace.

Responses have also been widely recorded in Tasmania on pastures on podzolic soils and on pastures and root crops such as potatoes on krasnozems (Fig. 8).

Responses by legumes to potassium are also recorded by Andrew and Bryan (1955) on meadow podzolic (low humic gley) soils for the coastal lowlands of southern Queensland. This soil responded to phosphorus, nitrogen, calcium, potassium, copper, zinc, molybdenum, and boron in descending order of importance.

The soil profile consists of about 16 inches of gray to white sandy surface horizons over mottled sandy clay subsoils. Reaction values were between pH 5 and pH 6 with phosphorus = 0.001 per cent throughout the profile. Nitrogen decreased rapidly from 0.036 per cent in the surface 5 inches where exchangeable potash was 0.04 m.e. per cent.

A history of the development of potash deficiency appears to be the case on podzolic and lateritic podzolic soils of the southwest of Western Australia where responses of pastures to applications have been recently reported by Fitzpatrick and Dunne (1956). It would seem that the appearance of potash deficiency was inevitable on these soils for analytical

data reveal low initial amounts. These soils have in the past responded to superphosphate and to copper.

The great bulk of the soils in the area are derived from a regional oc-

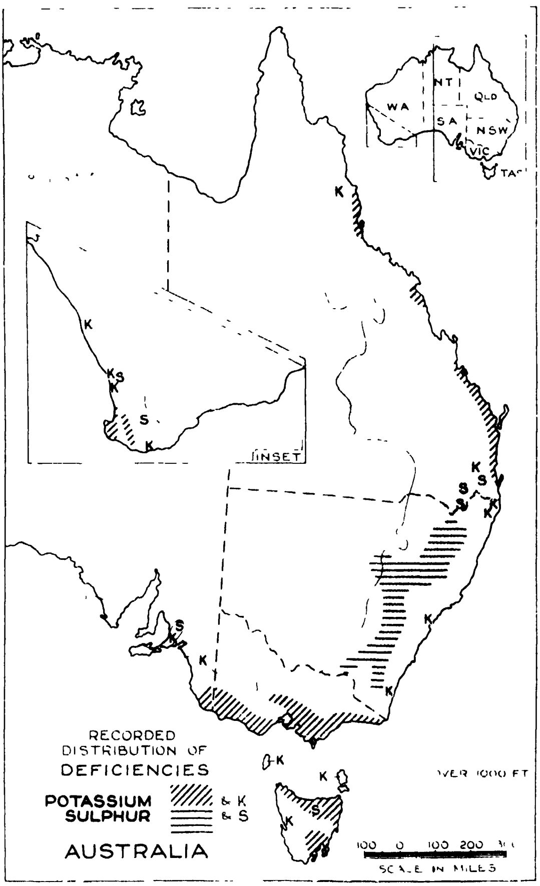

FIG. 8. Recorded distribution of deficiencies of potassium and sulphur in Australia. Sulphur deficiency is widely recorded but is not continuous in the hachured area in New South Wales.

currence of laterite. The soil described below, the Mungite sandy loam, has been formed on the kaolinitic mottled zone exposed by mild dissection of the mantle of laterite. The A_1 horizon consists of 3 inches of dark gray sandy loam with moderate amounts of organic matter, pH 5.8, nitro-

gen = 0.25 per cent, with 0.16 m.e. per cent of potassium in a total of 4.18 m.e. per cent exchangeable metal ions. The A_2 horizon is a light gray sandy loam about 6 inches deep; the B_1 horizon is a light gray sandy clay loam, brittle when dry and plastic when wet; the B_2 horizon is a light gray and yellow mottled sandy clay with red inclusions and with some lateritic gravel, passing sharply to a C horizon of similarly colored gritty subplastic clay.

The marginal potassium status of great areas of Australian soils makes the increased use of potassium fertilizer inevitable.

B. Sulfur Deficiency

For many decades the deficiency of sulfur on various Australian soils was obscured by the general use of superphosphate, containing 13 per cent sulfur, as a phosphatic fertilizer. Sauchelli (1950) has made a similar point that if nonsulfur-containing phosphatic fertilizers supplanted superphosphate in the United States sulfur deficiency would appear on many sites.

Sulfur deficiency is now widely recorded in New South Wales. It has shown up in pot tests on a number of Victorian soils and there are occasional field records in other states (Fig. 5), but the picture for Australia as a whole is still incomplete. The usual approach is to seek a segregation of the separate effects of phosphorus and of sulfur, which are confounded when superphosphate is used as a fertilizer. The result may be the definition of a simple phosphorus deficiency, but there are varying degrees of dependence on sulfur, including soils on which the entire response to superphosphate has proved to be due to sulfur.

Reference has already been made in Section III, B to McLachlan's (1955) survey through pot experimentation of phosphorus, sulfur, and molybdenum deficiencies in 32 virgin soils of eastern Australia. The mean percentage increases in yield of subterranean clover due to sulfur in the presence of both phosphorus and molybdenum were: red podzolic soils, 190 per cent; yellow podzolic soils, 105 per cent; krasnozems, 86 per cent; and black earths, 164 per cent.

Although McLachlan gained a strong positive correlation (+0.79) between the magnitude of the responses secured and the pH value of the soil, he found no correlation with the parent material (granitic, basaltic, or sedimentary) nor with the climate (temperature or rainfall) of the collection sites.

The potential incidence of sulfur deficiency will depend, among other factors, on the balance between the sulfur received in the rainfall and that lost in drainage from the soil. It is of interest to note that the limited data at present available on Australian rainfall show an unusually low sulfur

content. Eriksson (1956) gives 10 kg. per hectare (8½ lb. per acre) as a modal world value for the sulfur content of unpolluted rainfall. In contrast Turton quoted by Rossiter (1952) gives a figure of less than 1 lb. per acre per year at Kojonup, Western Australia, a town only 100 miles from the coast. In a more detailed study of the rainfall at a number of Victorian centers, Hutton and Leslie (1958) found values ranging from 3 to 7 lb. at the coast to less than 2 lb. per acre over most of the state. The exact significance of rainfall in the sulfur status of Australian soils needs fuller examination.

A severe triple deficiency of phosphorus, sulfur, and molybdenum was recorded on podzolic soils on the southern tablelands of New South Wales (Anderson and Spencer, 1949) and these three elements seem to be of predominant importance over a large area of that state.

The contrasting significance of phosphorus and sulfur in various regions of Australia and the character of the affected soils is shown by the following examples:

On the Kojonup gravelly sand, a lateritic podzolic soil, Rossiter (1952) obtained the following response to sulfur and phosphorus:

	Nil	S	P	P + S
Cwt. pasture dry matter per acre	6 8	13.1	35.8	40 9

This soil consists of an A_1 horizon of brownish gray gritty sand with organic matter and moderate amounts of ferruginous gravel, pH 6.2, to a depth of 2 inches, overlying an A_2 horizon of light gray-brown gravelly sand, pH 6.5, to a depth of 19 inches, overlying a B horizon of red-brown, yellow-brown, light gray mottled gritty clay, pH 5.0, to a depth of 34 inches, overlying a C horizon of kaolinitic clay, pH 4.2, light gray in color and with red and yellow mottling, overlying granitic gneiss.

On a black earth, with a surface soil of silty clay loam of reaction value about pH 8, derived from basalt, near the Liverpool Range in northern New South Wales, Hilder and Spencer (1954) obtained a response to sulfur on naturally occurring pasture medics (annual *Medicago* spp.) which showed no additional response to phosphorus :

	Nil	S	P + S
Cwt. medics dry matter per acre	3 6	20.4	20.3

This kind of result is found fairly commonly on black earths derived from basalt, similar results being obtained near Cooma in southern New

South Wales (McLachlan, 1952) and on the black earths of the Darling Downs in Queensland. For example, on a black earth soil composed of very dark gray clay of granular structure, pH 6.5., overlying brown, light brown, and yellow-brown well-structured clays, slightly calcareous, to a depth of 4 feet, Andrew *et al.* (1952) obtained the following result in a pot experiment with *Paspalum scrobiculatum*, there being no response to phosphorus:

	Nil	N	S	N + S
Yield, g. dr. wt.	0.5	2.5	2.2	3.9

Again on a shallow krasnozem derived from basalt at Armidale in New South Wales, Hilder (1954) obtained a major response to sulfur. Here the profile consists of a friable brown clay loam, pH 6.2, over a red clay, pH 5.8, from a depth of 8 inches.

	Nil	P	S	P + S
Cwt. clover dry matter per acre	12.8	15.7	33.1	26.2

Thus the incomplete picture at present available is of a dual deficiency of phosphorus and sulfur on various podzolic and lateritic podzolic soils, or of a strong sulfur deficiency unassociated with any phosphorus deficiency on black earths and on some podzolic soils. McLachlan's (1955) pot experiments, however, also show that red-brown earths may be sulfur deficient.

An aspect of particular significance in Australia is the relationship of sulfur supplied in fertilizer to the increment in organic matter under the influence of clover growth on soils of initially very low organic matter status. Reference has been made to Williams and Donald (1957) finding on a podzolic soil that the ratio of carbon, nitrogen, sulfur, and phosphorus in both the virgin and incremental organic matter was 155 : 10 : 1.4 : 0.7. Since the ratio of S : P in superphosphate is 1.3 : 1, and in the soil organic matter was 2 : 1 sulfur is likely to be the limiting factor in the build-up of organic matter, even where phosphorus is the element more acutely limiting plant growth on the virgin soil.

C. Magnesium Deficiency

Magnesium deficiency is comparatively rare in Australia (Fig. 9). As would be expected, it has been recorded only on some of the more acid soils or where frequent applications of the more acidic fertilizers have

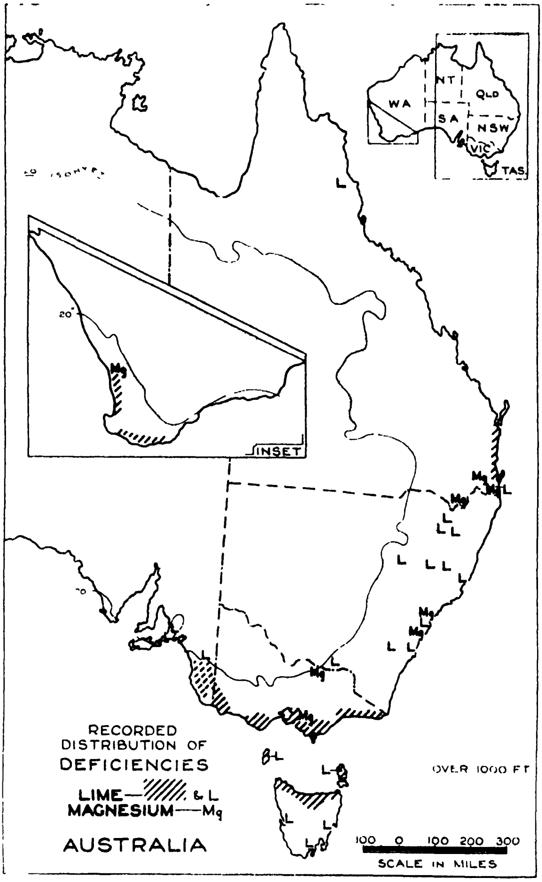

FIG. 9. Recorded distribution of magnesium deficiency and responses to lime in Australia. Areas in which responses to lime are largely due to an increase in the availability of molybdenum are not shown. On much of the area depicted, lime is used to secure effective nodulation of legumes in pasture establishment.

been made. This comparative rarity is not surprising, for Australian soils as a whole, including a large proportion of the more leached soils, contain an unduly large proportion of magnesium in the exchangeable metal ions. This is a somewhat singular feature of Australian soils and was noted quite early by Prescott (1931). A recently described example is the Grainger loamy sand, a podzolic soil mapped by Northcote and Tucker (1948) on Kangaroo Island, South Australia. This soil has a surface horizon (0–4 inches) of pH 5.7 with exchangeable calcium 1.92 m.e. per cent

and magnesium 1.12 m.e. per cent; the subsoil clay (10–23 inches) of pH 5.8 contains 0.24 and 3.18 m.e. per cent, respectively. This marked increase in the proportion of exchangeable magnesium in the B horizon is indicative of a somewhat solodic character impressed on many Australian soils, and may have its origin in part in the cyclic oceanic salt characteristic of Australian rain.

Another factor precluding the appearance of magnesium deficiency in the more acid soils has been the use in some localities of lime on sown pastures and on horticultural crops such as apples. Much agricultural lime contains a significant proportion of magnesuim carbonate.

However, magnesium deficiency has been recorded in citrus, vegetables, and pastures on podzolic soils on shales and sandstones near Sydney, New South Wales; in citrus, apples, and pears on podzolic soils, and on a deep sandy red-brown earth receiving much ammonium sulfate in Victoria; and in citrus on alluvial soil, in apples on podzolic soil, and in pastures on a krasnozem on rhyolite in southern Queensland; and in apples and citrus on lateritic podzolic soils of restricted drainage near Perth in Western Australia.

The affected krasnozem soil in Queensland occurs on the Springbrook plateau where rainfall is 160 inches per year; Von Stieglitz (1951) describes it as follows: Dark brown loam of crumb structure to a depth of 6 inches, underlain by red-brown loam of nutty structure to 18 inches, followed by red-brown blocky loam to clay loam to 24 inches, over red clay to 36 inches, the whole resting on rhyolite.

No analytical data are available but in a series of field experiments on pasture the best result was obtained with superphosphate and dolomite, rather than superphosphate and lime or superphosphate alone.

D. Responses to Lime

The role of lime in Australian agriculture is not yet fully resolved, but at the present time at least three distinct effects can be recognized from the use of this fertilizer.

The effect of lime in raising pH and increasing the availability of molybdenum is discussed in Section VII, D. When this effect became known the responses being gained to lime on pastures in many districts were proved to be due in fact to molybdenum deficiency. In Tasmania for example, all lime responses by established pastures in which legumes are already nodulated can be equaled or exceeded by the use of molybdenum (Paton, private communication). Lime responses of varying magnitude can be secured on all acid, molybdenum-deficient soils but the use of lime is less effective and more expensive than the direct use of molybdenum. These areas are not shown on the map of lime responses (Fig. 6).

The most important use of lime in Australia at the present time is to secure satisfactory nodulation and establishment of legumes on acid soils (Anderson and Moye, 1952). There are many such areas across Australia in which clover sown only with superphosphate and trace elements will fail partially or completely due to defective nodulation combined with the extremely low nitrogen status of the soil. This use of lime accounts for most of the areas shown in Fig. 6.

The amount of lime required for this purpose is quite small, approximately two cwt. per acre, with a considerable gain in efficacy if the lime is drilled with the seed rather than broadcast. This practice is proving of importance in pasture establishment on podzols and podzolic soils, derived from a wide range of parent materials, and usually within the pH range of 4.0 to 5.5.

Spencer (1950) conducted a pot experiment on a yellow podzolic soil of sedimentary origin, known to require lime for satisfactory legume establishment. He found that nodulation and yield were satisfactory only if both increased pH and additional calcium ions were provided. This is clearly illustrated by the interaction between calcium sulfate and magnesium hydroxide:

	Nil	$CaSO_4$	$Mg(OH)_2$	$CaSO_4$ + $Mg(OH)_2$
No. of nodules per pot	51	6	13	656
Yield per pot (g.)	0.54	0.58	0.04	1.89

This soil has a pH of 4.9–5.1 throughout the surface 12 inches. A brownish-gray loamy fine sand with organic matter (0–3 inches) overlies a light yellowish-gray sandy clay with yellow-gray mottling, and with light quartz grit.

There are also indications from other states that the nodulation response to light lime dressings is associated with calcium status as well as soil reaction.

An interesting interaction of lime and molybdenum is recorded by Anderson and Moye (1952) on an acid soil of the southern tablelands of New South Wales. Here a light dressing of lime is essential to permit nodulation; in addition either a heavy dressing of lime or a dressing of molybdenum is needed to provide adequate molybdenum for nitrogen fixation. This interaction is shown by the following yields of subterranean clover on a podzolic soil (pH 4.5–4.7) on the tablelands of New South Wales:

Lime (cwt. per acre)	0	½	1	2	4	8	16
Yield—cwt. dry matter per acre							
−Mo	0.3	2.1	3.2	3.7	6.3	9.4	12.9
+Mo	0.3	6.0	6.7	11.3	14.0	15.0	16.0

This work led to the commercial practice on these soils of using molybdenum-superphosphate together with about two cwt. lime drilled with the seed.

Loneragan *et al.* (1955) found that the quantity of lime required for nodulation could be further substantially reduced by complete localization around the seed. Seed pelleted with lime, 5 lb. of lime on 10 lb. of seed, gave comparable results to those secured by the use of 2 cwt. lime per acre drilled with the seed, namely a fivefold increase in first year yields.

One of the little understood features of many of these soils on which lime improves nodulation is that even without lime, the nodulation and the growth of clover will gradually improve to normal over a period of years. In other instances however the use of lime seems imperative.

A third effect of lime can be recognized when there is a simple deficiency of calcium. Here much heavier dressings may be necessary. Millikan (1944) showed that the disease "withertop" of flax occurring over a substantial area of southern Victoria is due to calcium deficiency. This deficiency is induced by waterlogging of the soil which is sometimes calcareous in the subsoil. Identical symptoms were produced in calcium-deficient sand cultures. The affected soils are all acid, pH 5.3–6.3, and have a high percentage clay, with 88–155 parts available CaO per 100,000. The following responses were secured at Lismore, Victoria, on a fine-textured soil with gray clay-loam to clay 0–24 inches; yellow clay 24–36 inches, and, surprisingly, calcareous rubble below 36 inches.

	Per cent of flax plants affected by "withertop"
1 cwt. super	88
1 cwt. super + 3 cwt. slaked lime	60
1 cwt. super + 1 ton slaked lime	6
1 cwt. super + 1 ton ground limestone	6

Calcium deficiency is also among the multiple deficiencies of the gley soils of the coastal south eastern Queensland, described in Section VI, A.

There remain other responses, none of them particularly extensive, in which the effect of the lime has not been precisely determined. Vegetables

grown on acid swamp soils in the Albany district and on acid peat soils such as those of Herdsman's Lake near Perth, Western Australia, respond to lime. Many of these soils contain marcasite and other sulfides, which, following drainage, oxidize to give iron oxide and sulfate and free sulfuric acid; pH values of 2 or 3 are not uncommon, with one record of pH 0.52. These soils have been described by Teakle and Southern (1937) and include, for example, the Njookenboro peat.

This soil consists of a dark-colored, iron-stained peat from 6 to 16 inches thick with a field capacity of about 400 per cent water, overlying a pinkish dark gray-brown gelatinous peat more or less fibrous with roots. A calcareous layer may occur in the subsoil as a pink and light gray marly peat. Reaction values range from pH 1.2 to 4.3 in the upper peat horizons.

Potato responses in Tasmania, of the order of 20 per cent increase in yield, have been recorded by J. H. Wilson (1949) following the application of lime to meadow podzolic soils, such as the Huon series, described by Stephens and Taylor (1935), and on krasnozems developed on basalt (see VII, D.).

Responses of undefined character have also been recorded for peanuts, lucerne, and pastures in Queensland, pastures (other than a molybdenum effect) at a few centers in New South Wales, on peas on alluvial and krasnozem soils in Tasmania, and on vegetables on podzolic soils around Melbourne.

Though no figures are available the total use of lime in Australia is relatively small, particularly in view of the considerable area of podzolic soils. However, considerable proportion of Australian podzolic soils, compared to their counterparts in Europe and America, exhibit somewhat anomalous chemical features. These include higher than usual reaction values, often around pH 6 in the A horizon, with correspondingly high proportions of exchangeable cations.

For example the meadow podzolic soil, the Riddoch sand described by Stephens *et al.* (1941), in its sandy A_1 horizon of pH 6.0 contains 3.56 m.e. per cent of exchangeable calcium and 0.95 m.e. per cent of magnesium. In the clay of the B_1 horizon of pH 6.5 there are 18.03 m.e. per cent of exchangeable calcium and 4.70 m.e. per cent of magnesium.

VII. Trace Element Deficiencies

A. Copper Deficiency

Copper deficiency (Fig. 10) both of plants and of animals is widely recorded in southern Australia; work on long known diseases of livestock preceded studies on plants. Lines (1935) and Marston *et al.* (1938)

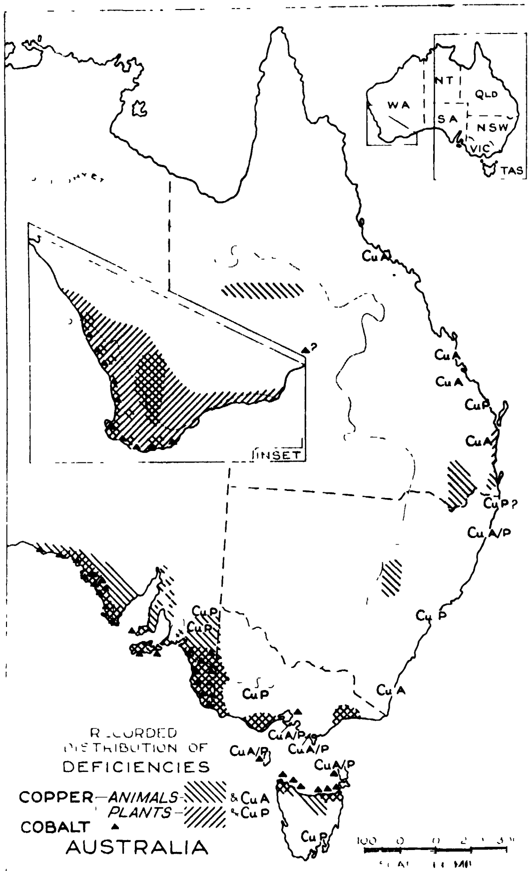

FIG. 10. Recorded distribution of responses of plant and animals to copper and animals to cobalt in Australia.

showed that "coast disease," which affects sheep and cattle on the coastal dunes of South Australia, Tasmania, and Western Australia, is due to a dual deficiency of copper and cobalt. Bennetts (1937) in Western Australia demonstrated that enzootic ataxia (rickets) of lambs and falling disease of cattle (1941) are due to a simple deficiency of copper.

Copper deficiency has been recorded on a great diversity of soils variously affecting sheep and cattle, pasture species, and a considerable variety of field and horticultural crops (Fig. 11). It is always associated with phosphorus deficiency and commonly with deficiencies of zinc, molyb-

FIG. 11. The effect of the treatment of grapevines with copper. The upper picture shows the stunted growth of 10-year-old vines on deep sandy podzolic soils at Gin Gin Western Australia. In the lower picture the vines have been treated with soil dressings and sprays containing copper compounds. (From Dept. of Agriculture, Western Australia.)

denum, and potassium, but the affected soils show no known common character. Where stock are affected, the syndrome varyingly includes unthriftiness, scouring, and falling disease (sudden death from heart failure) in cattle; and unthriftiness, ataxia of lambs, and "steely" wool in sheep (Fig. 12). These ailments can be overcome either by direct administration of copper or, more satisfactorily, by the use of copper as a fertilizer. Use as

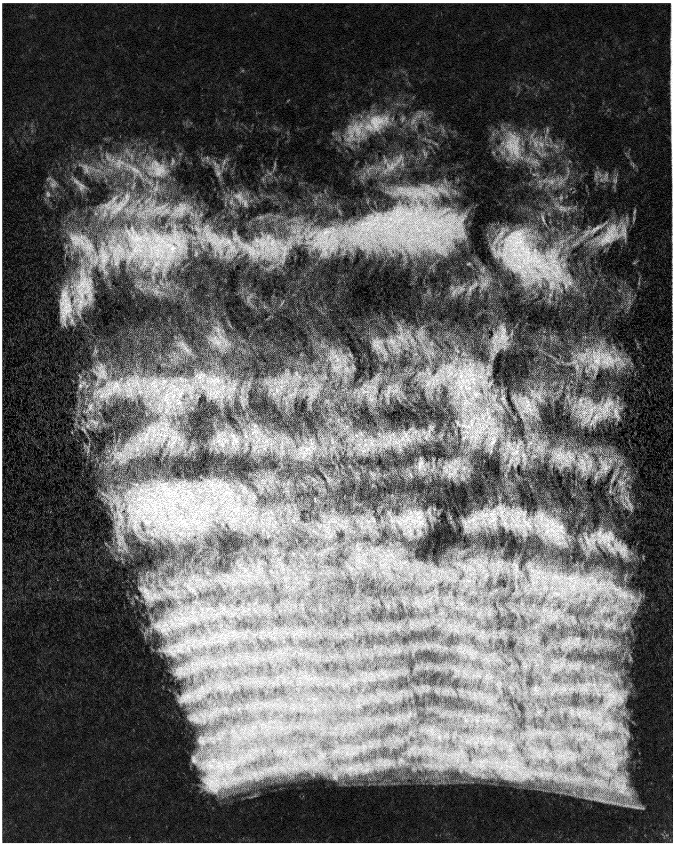

FIG. 12. The distal part of these wool fibers shows steely sheen and lack of crimp which developed when the sheep was grazing on copper deficient pasture. Crimp returned abruptly when the ewe, though still maintained on the same pasture, was dosed with the equivalent of 10 mg. of copper per day. (From H. R. Marston.)

a fertilizer commonly gives not only a better control through the herbage but also improved production by the pasture.

Plant growth as well as animal health presented serious problems on the "coasty soils" referred to above. Of the cereals, only rye (*Secale cereale*) could be grown; wheat and oats showed severe foliar symptoms and produced little grain if they headed at all. The pasture was dominated by two inferior Mediterranean annual grasses (*Bromus madritensis* and *Lagurus ovatus*). Apart from occasional stunted plants of *Swainsona* (a

native genus) and *Melilotus indica* the pasture was legume free. All attempts to establish superior pasture plants using superphosphate as the fertilizer had failed. Investigation of this problem at Robe, South Australia, led to the finding that copper was acutely deficient for plant growth (Riceman and Donald, 1938). When copper sulfate at 7 lb. per acre was used in conjunction with superphosphate, it gave spectacular success in the production of both cereals and pasture legumes, notably *Medicago sativa* and *M. lupulina*.

The Robe soil, which is an aeolian calcareous sand high in comminuted shell fragments and with up to 80 per cent $CaCO_3$, has a reaction of pH 8.5 in the gray-colored surface soil. This rises to about pH 9 in the featureless yellow calcareous sand of the remainder of the profile. A similar soil, the Currie calcareous sand of King Island in Tasmania has exactly the same plant and animal problems and has been described by Stephens and Hosking (1932). Extensive analytical data were there presented. The surface soil contains on the average 0.29 per cent nitrogen and 0.07 per cent phosphorus.

At Robe the response recorded by Riceman *et al.* (1940) with oats in an adverse season was as follows:

	−Cu	+Cu
Oats, grain in lb. per acre	44	452

On the Laffer sand, a solonetzic soil described by Taylor (1933), in the upper southeast of South Australia, Riceman (1948) obtained the following results (yields in cwt. of dry matter per acre) with copper, phosphorus, and zinc:

Species	Nil	P	P + Cu	P + Cu + Zn
Subterranean clover				
(1 cwt. super per acre)	1.5	5	7	26
Lucerne (8 cwt. super per acre)	0.5	7 5	16	16

The contrasting response to copper and zinc by these two species is typical.

The Laffer sand is a solidized solonetz with characteristic bleached A horizons and a B horizon often showing accumulation of sodium in the exchange complex. The A_1 horizon consists of gray sand to a depth of 3 to 4 inches; the A_2 horizon is composed of light gray to white sand; and the B horizon which is sharply defined from the A_2 is composed of yellow or grayish-yellow sandy clay-loam to clay. At a shallow depth of some-

thing over a foot the profile rests on limestone. The A horizon is usually neutral in reaction while the B horizon has a pH as 8.4 with up to 21 per cent sodium in the exchangeable metal ions. In the A_1 there is 0.03 per cent nitrogen and 0.001 to 0.002 per cent phosphorus.

Anderson (1946) showed the pronounced effect of copper on pasture legumes on part of a neutral to alkaline fen, the Badenoch friable peat, described by Stephens (1943) in the lower southeast of South Australia. In an experiment also involving zinc, he obtained the following yields from a mixed pasture in which both direct responses and changing competitive relations were involved (Table XIV).

TABLE XIV

Responses of Mixed Pasture to Zn and Cu

Species	Nil	Zn	Cu	Zn + Cu
Phalaris tuberosa	8 5	16 1	8 0	10.5
Medicago sativa	1 9	0 9	16 6	15 9
Medicago lupulina	6 1	4.0	4 6	5 1
Other species	3 5	5 3	5 2	6 2
	20 0	26.3	34.4	37.7

The Badenoch peat consists of about 15 inches of black friable and granular peat over about 27 inches of black fine peat over a variable depth of black and brown mixed coarse and fine peat, the whole resting on calcareous sand or limestone. The surface soil which contains up to 40 per cent organic carbon has a nitrogen content usually greater than 2 per cent and a phosphorus content of 0.09 per cent. Reaction of the surface soil is usually above pH 7; the subsoil is slightly more acid but near the calcareous substrata values rise to about pH 8.

On the Plantagenet peaty sand, an acid peaty ground-water podzol, described by Hosking and Burvill (1938) in the southwest of Western Australia, Teakle *et al.* (1941) showed a severalfold response to copper by maize:

	−Cu	+Cu
Maize (tons green matter per acre)	2 2	8 3

The Plantagenet peaty sand consists of about 1 inch of black peaty sand over an A_1 horizon of dark gray sand with organic matter, an A_2 of light gray to white sand with brown staining, a B_1 horizon of dark brown sand indurated to form "coffee rock" and a C horizon of gritty sand, ce-

mented in the lower part. The whole profile is quite deep, up to 7 feet, and is waterlogged in the winter months. Reaction values are pH 4.2 in the surface and not above pH 5 in any part of the profile. Nitrogen content is 0.24 per cent in the A_1 horizon and there is only 0.0025 per cent phosphorus in the peaty sand.

On an acid swamp soil at Lake Chandler 35 miles north of Perth (Teakle and Burvill, 1941), copper gave a large increase in potato yields from 0.5 to 3.2 tons of potatoes per acre, and in Sudan grass yields from a negligible production to 1.2 tons per acre. The soil is of diatomaceous material and sand darkened by organic matter in the surface; there is a hardpan of white cemented diatomaceous earth at a depth of a few feet. The reaction of the soil averages pH 5.

An example of response (Teakle *et al.*, 1943) on a deep sandy soil is provided on the Whakea sand at Gingin, Western Australia, where vines showed very poor growth. Copper sprays, not previously used for disease control, or copper application to the soil gave marked increase in growth, as shown by the weight of prunings, 10 ounces in the control and 45 ounces in copper-treated vines. The soil description by Hosking and Greaves (1936) indicates a very weakly developed red podzolic soil sedentary on sandstone. The profile is several feet in depth, reaction between pH 6 and pH 6.5 throughout; the texture rises gradually from sand to loamy sand.

Dual deficiency with other trace elements is commonly recorded. Examples have already been cited of copper and zinc deficiency, while the following example shows a dual deficiency of copper and manganese on a marly, marsh soil near Albany (Teakle *et al.*, 1941):

	Nil	Mn	Cu	Mn + Cu
Yield of potatoes (tons)	7.2	10.1	7.0	11.6

In other instances dual deficiencies of copper and molybdenum occur, e.g. on a podzolic soil with a slightly acid (about pH 6.0) gray sandy loam surface at Wairewa in Gippsland, Victoria (Drake and Kehoe, 1954) where the yields of pasture with phosphorus and potassium basal were:

	Nil	Mo	Cu	Cu + Mo
Tons green matter per acre	5.5	4.9	6.4	8.3

Copper deficiency of citrus and apples is recorded on podzolic soils and of citrus on solenized brown soils in several states as shown in Table IV.

All states of the Commonwealth have now recorded copper deficiency of sheep and cattle. There is of course a considerable tendency for plant and animal deficiencies to be coextensive but this is by no means always so. In South Australia, mild copper deficiency of animals, commonly expressed as "steely wool" in sheep, extends to limits beyond those of the areas affected by plant deficiencies. In Western Australia on the other hand, it is the plant deficiencies which are recorded over far more extensive areas than are the animal deficiencies. In Queensland, known plant and animal occurrences are geographically almost independent.

These apparent anomalies may perhaps be explained on two main grounds. First, over considerable regions the livestock industry and crop (or sown pasture) industry have separate distributions. Grazing districts with native pasture are unlikely to record plant deficiencies. Secondly, the incidence of copper deficiency of animals is accentuated by high molybdenum content of the pasture and vice versa (Dick and Bull, 1945). This means that while the copper deficiency of plants is largely a reflection of the supply of available copper in the soil, this is only partially true of livestock deficiencies. Further the sulfate status of the diet in turn affects the influence of molybdenum on copper storage in the liver (Dick, 1953).

There is some tendency over the Commonwealth as a whole for areas suffering molybdenum deficiency of plants to be noncoincident with those affected by copper deficiency of animals, but there are exceptions even to this observation.

B. Cobalt Deficiency

Acute cobalt deficiency in sheep leads to loss of appetite, progressive wasting, anaemia, and symptoms of gradual starvation until death occurs (Fig. 13). With less acute deficiency, adult sheep may be unaffected but lambs will show typical symptoms, varying in effect from slight retardation of growth to 100 per cent mortality. Cattle are also affected. The fodder available to the animals may appear to be of excellent quality. Lee (1951) has defined the distribution of cobalt deficiency in Suoth Australia, where th edeficiency was recorded in 1935 (Lines 1935) and where the distribution is now fairly well known. In that state acute deficiency is confined to a narrow coastal band of calcareous "shell-sand" dunes, and soils on shell-beds. Though only a few miles deep, the affected coastline is some 800 miles in length. A typical calcareous dune soil at Robe, South Australia is described in the section on copper deficiency.

Subacute deficiency is much more widespread and affects almost the whole of the southeast of the state, soil zone J. In that region soils are of very diverse character, including terra rossa, rendzinas, and siliceous sandy podzolic soils. But Lee (1951) emphasizes their common origin from

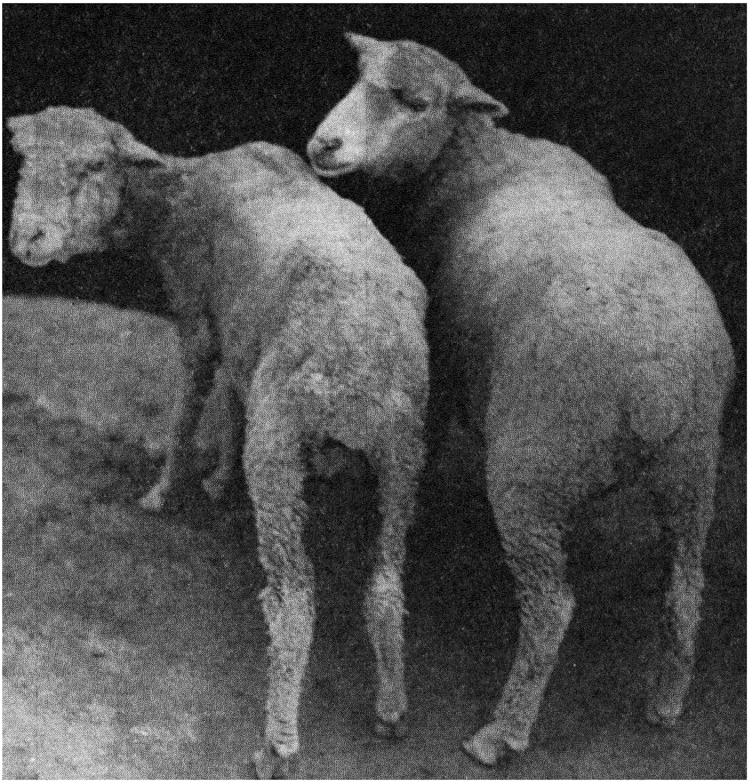

FIG. 13. These twin Merino ewes had grazed for 55 weeks on cobalt-deficient terrain in South Australia. During this period the ewe on the right received the equivalent of 1 mg. cobalt per day. The ewe on the left was untreated and developed symptoms of extreme cobalt deficiency. (From H. R. Marston.)

marine calcareous material. Terra rossa have been derived by leaching stripping and reweathering of consolidated dune limestone; the siliceous podzolic sandy ridges by extensive leaching and removal of the calcareous material; and rendzinas by development on polyzoal marine limestone and secondary calcareous deposits in interdune swales. Thus the common feature of cobalt deficiency is related to the original parent materials and scarcely at all to the present extremely distinctive profiles of the region.

The effect of oral supplementation with cobalt (1 mg. per sheep per day) is a marked improvement in general thrift and production. However, the current practice is the administration to each sheep of a five-gram

pellet of 90 per cent cobalt oxide and 10 per cent pipe clay, tableted and baked. This remains permanently in the reticulum, releasing to the rumen contents between 0.1 and 1.0 mg. per day (Dewey *et al., 1958*).

In Western Australia early work showed that "Denmark Wasting Disease" was caused by cobalt deficiency (Underwood and Filmer, 1935). Affected soils include calcareous and siliceous sands of the coastal fringes; podzolic soils of gray and brown sandy loams over yellow clay and lateritic podzolic soils in the Denmark-Northcliffe area; and gray sands with lateritic ironstone gravel over clays resting on decalcified Miocene sediments in the Albany and Many-Peaks district.

Cobalt deficiency in Tasmania occurs in less acute forms on krasnozems and podzolic soils. It is most acute on King Island, largely on calcareous aeolian sands but with some sandy podzols on Pleistocene deposits also deficient. Other podzolic soils such as the Pegarah sandy loam on Cambrian and Ordivician metamorphosed sediments and the Camp Creek sandy loam on granite are capable of curing the disease (Stephens and Hosking, 1932).

Except for recent indications of a minor nature in Queensland and Victoria, there have been no records of cobalt deficiency in those states or in New South Wales. It would seem odd that the affected region in the lower southeast of South Australia, soil zone J (Fig. 5) is bounded by the Victorian border but presumably quite by chance the political boundary approximately coincides with the line dividing soil zone J from soil zones F and K, both of which are unaffected.

C. Zinc Deficiency

Zinc responses in Australia (Fig. 14) were first recorded with the application of overseas findings on the cure of mottle leaf in citrus to podzolic soils in Western Australia by Pittman and Owen (1936) and to lighter textured solonized brown soils in South Australia (Strickland, 1937) and New South Wales (Benton, 1937). The Winkie sand, an example of this latter soil at Waikerie in South Australia, is highly regarded for citrus production, but mottle leaf in citrus and little leaf on other horticultural crops has been commonly recorded. According to Herriot and Johnston (1941) Winkie sand has the following characteristics:

The surface soil is a brown to reddish-brown sand or coarse sand to a depth of 18 inches, the subsoil a light brown or reddish-brown sand to a depth of 42 inches, underneath which lies a light brown sand or sandy loam with slight lime to a depth of 84 inches; this overlies similar materials to depths of up to 20 feet. Reaction values throughout the profile are alkaline and commonly reach pH 9 or higher. The surface soil contains up to 0.036 per cent nitrogen and 0.015 per cent phosphorus.

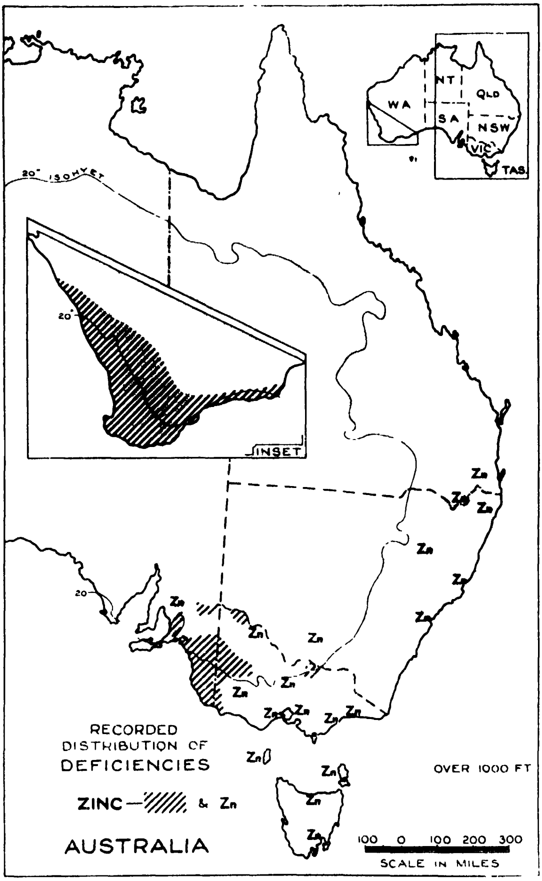

FIG. 14. Recorded distribution of deficiency of zinc in Australia. Zinc deficiency is widely recorded but is not continuous in the hachured area in Western Australia.

Millikan (1938) recorded a marked response by wheat on the gray soils of heavy texture of the important wheat-growing Wimmera district of Victoria which extends into the Tatiara district of South Australia:

	Bu. per acre	
	P only	P + Zn
At Nhill, Victoria	29.1	38.5
At Salisbury, Victoria	47.4	56.8

A typical profile described by Blackburn *et al.*, (1953) from near Bordertown in South Australia has the following features:

The surface inch consists of mellow crumbly clay, weakly laminated, pH 7.9; the next inch gray, dense sandy clay with cloddy structure, pH 8.2; then 12 inches of yellowish gray, tough cloddy sandy clay pH 8.6 to pH 8.8; then considerable amounts of lime for some depth.

Zinc deficiency has now been recorded on citrus, deciduous fruits, vines, *Pinus* species, wheat, oats, flax, and grass and legume pasture species. Some of the soils on which a dual deficiency of zinc and copper occur have been described in Section VII, A, e.g. the Laffer sand and Badenoch friable peat. Responses have also been recorded, e.g. dieback in flax, on the calcareous gray soils and black earths which sometimes occur with the red-brown earths; typical red-brown earths are not zinc deficient for flax although occasional horticultural crops do respond to zinc treatment. The following response was given by flax on a black earth at Saddleworth, South Australia (Adam and Piper 1943):

	P	P + Zn
Lb dry matter per acre (half grown)	710	1240

Zinc deficiency is widespread on the lateritic podzolic soils of the so called sand plains of Western Australia. Dunne *et al.* (1949) record responses on typical sandy soils with ferruginous gravel of reaction values pH 5.5 to pH 6 overlying laterite and yellow and brown clays. For example an experiment with oats gave the following result:

	P	P + Zn	P + Zn + Cu
Oats, bushels per acre	5.9	21.2	22.6

A contrasting soil type, a highly calcareous aeolian soil at Dongarra in Western Australia, as described by Dunne and Throssell (1948) gave the following results on a dark brown fine loamy sand containing about 50 per cent lime and of pH 8.5:

	P	P + Cu	P + Zn	P + Zn + Cu
Bushels per acre of wheat	17.3	20.7	20.7	31.1

Zinc has played a major part in pasture development especially on the lateritic podzolic soils, deep sandy and calcareous soils of Western Aus-

tralia and on solodized solonetz, podzolic soils, rendzinas, and other calcareous soils in South Australia. On all these soils zinc has commonly been critical in the establishment of legumes, as is illustrated by the results of Riceman (1948), described in Section VII, A.

In all southern states zinc deficiency has also been recorded on pines, especially *Pinus radiata*. It may, when acute, disastrously affect tree growth and has shown up very commonly in the second crop of trees. It is readily controlled by spraying with a 2 per cent solution of zinc sulphate. The Mount Burr sand, an extensive yellow podzolic soil of the southeast of South Australia, is commonly affected. It has been described by Stephens *et al.* (1941) and has the following profile:

The A_1 horizon consists of about 8 inches of gray, noncoherent sand with moderate amounts of coarse organic matter; the A_2 horizon of up to 2 feet of light gray sand; the A_3 horizon of up to 5 feet of light yellow to yellow sand; the B_1 of approximately 1 foot of yellow-brown cemented gravel and sand and the B_2 about 1 foot of yellow-brown structureless sandy clay-loam to sandy clay. The parent material is a leached aeolian sand and the reaction value varies around pH 6 throughout the profile. A surface soil for example was pH 6.6 and contained 0.044 per cent nitrogen and 0.005 per cent phosphorus.

It will be seen from Table II and from the soil descriptions that while zinc deficiency most commonly occurs on alkaline soils, it is also recorded on soils of neutral or acid reaction, and that the affected soils are of a grossly diverse character. The most common associated deficiencies are phosphorus, copper, and manganese.

D. Molybdenum Deficiency

Molybdenum deficiency was first recorded in Australia in the field on a lateritic podzolic soil at Meadows, South Australia (Anderson, 1942). Subterranean clover fertilized with superphosphate had consistently failed, except on small areas where fallen trees had been burnt. Spectrographic analysis of the wood ash of the pasture plants growing in these healthy patches showed a high molybdenum content; this element was therefore included in a trace element trial. Ammonium molybdate at 1 lb. per acre on the affected areas gave a spectacular increase in production, raising the yield of clover from 2.5 cwt. to 26.6 cwt. per acre. In the following year molybdenum response was recorded in Tasmania (Fricke, 1943, Stephens and Oertel, 1943).

Molybdenum deficiency of pastures has now been recorded over a very considerable area of New South Wales, Victoria, and Tasmania with less extensive but important occurrences in other states (Fig. 15). The fertilizer commonly used is molybdenum–superphosphate, containing 1½

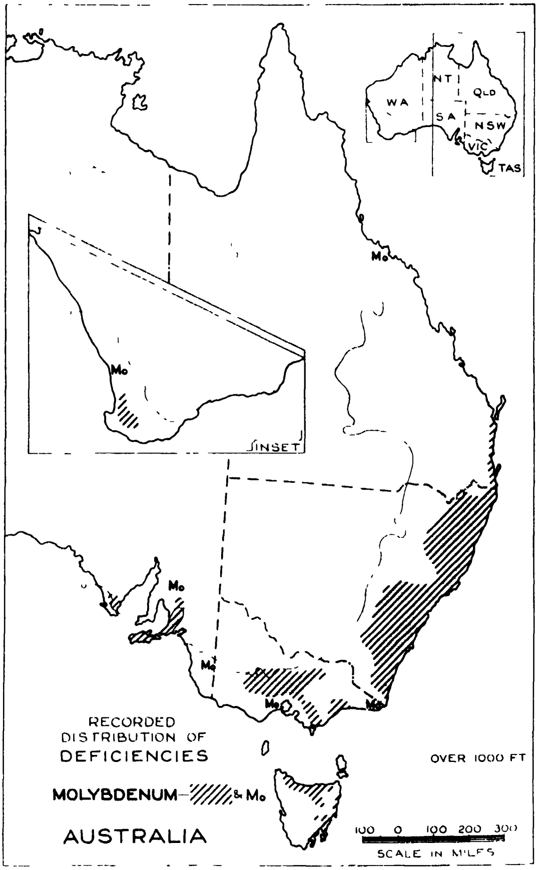

FIG. 15. Recorded distribution of deficiency of molybdenum in Australia. Molybdenum deficiency is widely recorded but is not continuous in the hachured area in New South Wales.

lb. of molybdenum trioxide per ton of superphosphate, so that a dressing of 1½ cwt. per acre gives an application of about 2 ounces of molybdenum trioxide per acre.

Australian pasture responses have invariably been due to response by the legume component. The molybdenum status is adequate for nitrate reduction in the host plant, but is insufficient for nitrogen fixation in the nodules (Anderson and Thomas, 1946). No response has been recorded by any pasture grass.

Responses by crops have been widely recorded. Whiptail of cauliflow-

ers has occurred in the vegetable (truck crop) producing areas around the capital of each state in the Commonwealth (e.g. Waring *et al.*, 1947). In addition responses have been recorded, many of them unpublished, on several other crucifers, by flax (Millikan, 1948), melons (e.g. Wilson, 1948a), pumpkins and cucumbers (e.g. Noonan, 1953), lettuce (Wilson, 1948b), peas (e.g. Fricke, 1944), by unnodulated beans (Wilson, 1949) and by oats, curing the locally named "Blue Chaff Disease" (Fricke, 1947).

Thus in terms of plant families, Australian deficiencies affect the Leguminosae (for nitrogen fixation), Cruciferae, Compositae, Cucurbitaceae, Solanaceae, Linaceae, Gramineae, and Leguminosae (for the host plant). On the basis of the study by Johnson *et al.* (1952) these last two groups indicate acute deficiency.

Because the deficient condition of pasture legumes is directly associated with defective nitrogen fixation, the symptoms in the field are those typical of nitrogen deficiency. These include paleness, small leaves, poor production, and often death. When molybdenum is applied it has the same effect as does an application of nitrogenous fertilizer, resulting in the development of a deep green color and a dramatic increase in production (Fig. 16). It is of importance to note that the tremendous responses

FIG. 16. The response of a pasture composed of subterranean clover and phalaris to molybdenum. Both plots received superphosphate at the rate of two hundredweights per acre: that on the left received ammonium molybdate at the rate of 2 ounces per acre. The soil is a brownish-gray clay loam, pH 6.2, near Stawell in western Victoria. (From Dept. of Agriculture, Victoria.)

to molybdenum by pasture legumes in many parts of Australia occurs only because of the very low nitrogen status of the affected soils. If the nitrogen status of these soils were higher, then legumes restricted in their nitrogen fixation by molybdenum deficiency would still make fair growth.

The principal occurrences of molybdenum deficiency are on lateritic and normal podzolic and solodic soils on a variety of parent materials, and on krasnozems on basalt. Some of the most spectacular responses recorded in Australia are those on the podzolic and solodic soils of the Central Highlands of Victoria (Newman, 1955), as shown by the following yields on a gray-brown loam, pH 6.1, and a brown fine sandy loam, pH 5.8 each over yellow clay subsoils:

Subterranean clover (cwt. dry matter per acre)

Fertilizer	At Buangor Victoria	At Elmshurst Victoria
Nil	8.8	9.8
P	8.6	10 0
P + Mo	43.6	59 5

A typical profile of these responsive Victorian soils is that for the Gowangardic loam (Downes, 1949). In this soil the A_1 horizon consists of 2 inches of brownish-gray loam, pH 5.6, containing 2.9, 2.5, and 0.43 m.e. per cent of calcium, magnesium and sodium in a total of 6.9 m.e. per cent exchangeable metal ions. The A_2 horizon to a depth of 5 inches is a light gray-brown loam to sandy loam, pH 5.6. The B horizon to 15 inches is a brown to red-brown heavy clay, pH 6.0, with slight grayish mottling and of small nutty structure when dry but sticky and plastic when wet; it contains 0.3, 8.0 and 1.46 m.e. per cent of calcium, magnesium, and sodium in a total of 10.2 m.e. per cent of changeable metal ions. The BC horizon below 15 inches consists of a brown to red-brown clay with pieces of decomposing sedimentary rock. The profile with its reversal of dominance of calcium and magnesium between the A and B horizons and rise in sodium with depth illustrates the solodic character impressed on many Australian soils of otherwise characteristic podzolic profile features.

Strong responses (Fitzpatrick, 1957) are also recorded on podzolic soils in Western Australia. There, on three sites, the mean yield with phosphorus alone was 8 cwt. per acre. Yield was increased by molybdenum to 21 cwt. per acre.

Responses are also recorded on a number of lateritic podzolic soils, as in the western part of the upper Goulburn region of Victoria (Newman, 1955) and the Adelaide Hills (Anderson, 1942). Analysis of the ironstone

nodules of these molybdenum deficient soils has shown (Oertel and Prescott, 1944) that these concretions have a high molybdenum content (e.g. 60 p.p.m. in ironstone nodules, 10 p.p.m. in soil), and it has been suggested that iron plays a part in the immobilization of molybdenum. The following is the profile of one of the soils, Kuitpo gravelly sandy loam (Rix and Hutton, 1953) on which clover yield was increased from 2 to 26 cwt. in the early work by Anderson (1942):

The A_1 horizon consists of 1 to 3 inches of gray to dark gray sandy loam with 13 per cent ironstone gravel, pH 6.2, nitrogen = 0.36 per cent, phosphorus = 0.025 per cent; the A_2 horizon 4 to 6 inches of gray-brown to yellow-brown sandy loam with 30 per cent of ironstone gravel; the B_1, 4 to 9 inches of dull yellow to yellow-brown friable sandy clay with moderate ironstone gravel; and the B_2C a considerable depth of yellow to yellow-brown clay with red, red-brown, and light gray mottling and with variable amounts of ironstone gravel.

On the other hand, in Western Australia, where lateritic podzolic soils are of wide occurrence, there are no records of responses on these soils other than two isolated instances recorded by Teakle (1944). Fitzpatrick (1957) in reporting other molybdenum responses in that state points out that responses are recorded in Western Australia largely where the ironstone layer has been weathered away, exposing the underlyng rocks, granites, gneisses, and schists, to weathering. "The resultant topography is that of a deeply dissected peneplain with characteristically steep slopes on which the molybdenum deficiency occurs" (Fitzpatrick, 1957). In terms of experience in other states the virtual absence of molybdenum deficiency on the lateritic podzolic soils of Western Australia is not understood.

Molybdenum deficiency has also been widely recorded on the more acid members of the krasnozem group in Tasmania and to a lesser degree elsewhere. A typical Tasmanian soil profile (Stephens, 1937) has the following features:

The surface soil consists of up to 12 inches of a dark brown friable granular clay with considerable organic matter; reaction pH 5.6, nitrogen = 0.39 per cent, phosphorus = 0.15 per cent. The deep and featureless subsoil consists of brown to red-brown friable granular to nutty clay which rests on weathered basalt.

All the foregoing soils are acid in reaction, but there are a few instances of responses on alkaline and even highly calcareous soils. Dunne and Jones (1948) record whiptail of cauliflowers, curable by molybdenum application, on calcareous sands of pH 8.2 and on calcareous loam containing 70 per cent calcium carbonate and of pH 8.6. There are also occasional records on black earths, calcareous soils of neutral to alkaline pH value.

This leads to the general question of the relationship of pH to molybdenum availability and response. Acid conditions lead to low availability of molybdenum and liming may give a sufficient improvement in availability to overcome the deficiency (Anderson and Oertel, 1946; Oertel *et al.*, 1946). There are however many acid soils on which lime at the rate of ½–1 ton fails to give the improvement in yield attainable through molybdenum application. The following examples (Newman, 1955) illustrate these frequent differences in the effect of lime, the figures being the yield of clover in cwt. per acre:

	P	P + Mo	P + lime[a]
Podzolic soil (pH 5.8)	10.0	59.5	21.3
Lateritic podzolic soil (pH 5.3)	6.4	23.3	25.8

[a] 10 cwt. per acre.

Thus the resources of total molybdenum available for liberation through increase in pH vary considerably. Commercially, of course, molybdenum is much simpler and cheaper to apply and is always as effective, unless lime is necessary for other reasons (see Section VI, D). Deficiency of total molybdenum is also clearly shown in the case of the soils of high pH values in Western Australia, already described.

Farmers are generally advised to exercise care in the application of molybdenum. A dressing of 2 ounces per acre seems adequate for a long period and a single dressing or only an infrequent repeat dressing, is usually advocated. Hosking (1957) reports instances in Victoria in which the use of molybdenum on swampy soils of marginal copper status has led to the death of lambs from induced copper deficiency.

Molybdenum deficiency is nowhere in Australia recorded as a simple deficiency. It is almost invariably associated with a deficiency of phosphorus, often together with sulfur or potassium, and in several areas also with a deficiency of copper. The following is a striking example of a triple deficiency of phosphorus, potassium, and molybdenum on heavily over-cropped land, but with prior applications of superphosphate, on the Cressy shaley clay-loam of Tasmania (Paton, 1956a):

	Yield of clover (cwt. air-dry per acre)			
	Nil	Mo	K	Mo + K
Superphosphate 1 cwt.	7.7	3.8	18.5	26.0
Superphosphate 3 cwt.	7.4	9.3	21.6	32.2

E. Manganese Deficiency

Manganese deficiency (Fig. 17) was the first of the recorded trace element deficiencies in Australia (Samuel and Piper, 1928), when "gray speck" of oats was cured by manganese application on the rendzina soils on calcareous volcanic ash of the Mount Gambier district and the ground water rendzina soils of the Penola district of South Australia. In some of the experiments, complete failure to produce grain was corrected by the use of manganese sulfate. Manganese deficiency has subsequently been

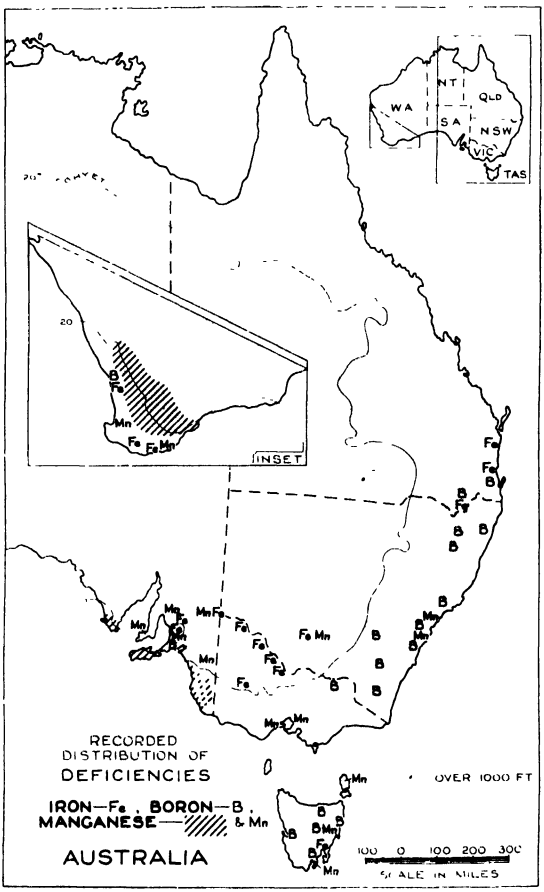

Fig. 17. Recorded distribution of deficiencies of manganese, boron, and iron in Australia.

recorded on pasture legumes as well as crops on these rendzina soils. Not infrequently it is essential for good pasture production. Other soils in South Australia now known to be affected in varying degree include the calcareous aeolian sands, the terra rossas, solodized solonetz, lateritic podzolic soils, and gray calcareous soils (Tiver, 1955).

A profile of the Millicent clay (Stephens *et al.*, 1941), a typical groundwater rendzina of the Penola district is as follows:

The surface soil which is up to 12 inches deep consists of a black friable clay of granular structure friability decreasing with depth pH 7.9, nitrogen = 0.43 per cent, phosphorus = 0.02 per cent. The next horizon also as much as 12 inches deep, consists of black cloddy clay with slight to medium amounts of lime; it overlies a gray calcareous clay resting somewhat abruptly on limestone. In the winter months a water table rises to the surface on some areas of this soil.

Manganese is not low in the Millicent clay (see Table II) but is unavailable on the better drained sites or where limestone dust from nearby roads is blown onto the surface soil ("road take-all," now known by the usual name "gray speck of oats").

Manganese deficiency is also recorded on some of the gray calcareous soils (Higgs and Burton, 1955). Here cereal crops may be acutely affected, as illustrated by an increase from 8.5 to 26.2 bushels of barley per acre due to the application of 20 lb. of manganese sulfate. Shallow calcareous aeolian sand in the same district, Corny Point, South Australia, is affected both by manganese and copper deficiency, as illustrated by the following yields (lb. per plot) of two pasture legumes with basal phosphorus:

	−Mn	+Mn	−Cu	+Cu
Medicago tribuloides	265	870	395	740
Medicago sativa	425	890	530	790

Alkaline fen soils (see Section VII, A for description) are yet another alkaline soil group affected by manganese deficiency. Here the difference in species reaction to multiple deficiencies is well illustrated (Anderson, 1946). These differences can be qualitatively summarized thus:

	Response to.	Principal response to:
Medicago sativa	Cu	Cu
Phalaris tuberosa (a grass)	Cu, Zn	Zn
Trifolium subterraneum	Cu, Zn	Cu
Trifolium repens	Zn, Mn	Mn

A restricted area of marly peat in Western Australia also shows copper and manganese deficiency with increases of 50–100 per cent in potato yields due to manganese application.

All the foregoing soils are naturally alkaline. On deep podzolic sands from Pliocene sediments near Melbourne, Victoria, with a natural pH of 5.0–5.8, manganese deficiency affecting vegetables (beet, cabbage, etc.) production has appeared when liming raises the pH to the relatively low value of 6.3. Twenty p.p.m. of available manganese in the unlimed soil may fall as low as 2 p.p.m. at pH 6.3. These soils characteristically have a gray sand with organic matter to 2 feet overlying light gray sandy clay. Relatively heavy application of manganese sulfate (60–100 lb. before plowing) is recommended (Skene and Kefford, 1955).

In Western Australia, manganese deficiency is of common occurrence over a wide area of the cereal belt though only limited patches, a few square yards or acres, are affected (Teakle and Wild, 1940). The sites are characteristic. They are rich in ferruginous gravel, especially in the subsurface layers; the surface sandy layer has a loose, ashy, or powdery structure; they are slightly acidic and of low inherent fertility. These soils appear somewhat unusual in that they have the surface features of lateritic podzolic soils but are alkaline below 12 inches and commonly show small to moderate amounts of calcium carbonate in the subsoil. They are being increasingly recorded in Australia and are referred to as calcareous lateritic soils (see Table I).

The following profile (Tinkurrin gravelly sand) is typical:

Depth (in inches)	Per cent gravel	pH	Description
0–3	14.9	6.3	Brownish gray gravelly, powdery sand
3–13	51.5	6.5	Pale yellow gray sharp, loose sand and loose round gravel
13–20	11.3	8.2	Similar but a sandy clay loam
20–35	10.1	8.4	Dark yellow sandy clay loam
35–42	12.5	8.3	Yellow and gray mottled sandy clay reddish at 40 inches

Many of the values for manganese in the Western Australian wheat belt are low, including a figure of 11 p.p.m. on a weakly responsive sandy, acid, lateritic soil at Wongan Hills.

Fruit production is affected in several localized areas by manganese deficiency. Fruits affected include citrus on podzolic soils and red-brown earths in New South Wales and citrus, apples, and plums on podzolized soils (lime induced) on the Bellarine Peninsula near Melbourne. Although

manganese is used on pastures on several soils in South Australia and Tasmania, it has not been of substantial importance in pasture development compared with molybdenum, copper, and zinc.

F. Boron Deficiency

The first record of boron deficiency in Australia was that by Carne and Martin (1937) who identified internal cork of apples and other disorders with deficiency of boron in podzolic soils (the Huon series) and in podzols (the Lucaston and Grove sands) in Tasmania. Other areas of similar soils in Tasmania have shown quite serious losses of swedes and turnips (Wade, 1956). The severity of the symptoms in apples increases with liming and this has also been observed by Paton (1956b) in pot experiments with subterranean clover on very acid sandy podzols.

The Lucaston sand as recorded by Stephens and Taylor (1935) is a podzol with the following morphological features:

The A_1 horizon of 8 inches depth is composed of dark gray sand with organic matter; the A_2 is a bleached light gray sand cemented into a hardpan and reaches to a depth of 18 inches. The B_1 horizon is composed of a black organic hardpan or of organic matter deposited in the upper part of the clay subsoil. The B_2 consists of yellow and gray mottled clay and this overlies at a depth of about 42 inches a yellow and gray C horizon formed from sedimentary rock. In virgin sites the reaction of the surface soil is about pH 4 and does not rise appreciably above this figure in the remainder of the profile. In orchards where lime is freely used reaction values are higher and quite variable.

Savage and Broadfoot (1937) identified boron deficiency in apples on podzolic soils at Kentucky on the northern tablelands of New South Wales. There have subsequently been numerous widely scattered records of boron deficiency on apples and vegetables throughout the coastal and highland regions of New South Wales and at isolated centers in all other states on podzolic soils, krasnozems, and alluvial soils.

Boron is a fertilizer of little consequence at present on pastures, though small field responses have been recorded on several podzolic soils in New South Wales (Anderson, 1952) and severe deficiency has been shown in pot cultures of acid peats and acid dune sands in Tasmania (Paton, 1956b).

G. Iron Deficiency

There are only limited records, mainly unpublished, of iron deficiency in crops on Australian soils. Nearly all occurrences concern horticultural crops, stone fruits, citrus, vines, pineapples, and tomatoes. In the great majority of cases, the deficiency takes the form of induced chlorosis due

to excessive lime in solonized brown soils, and in the more calcareous red-brown earths and gray soils of heavy texture of the irrigation areas of New South Wales, Victoria, and South Australia. There is an isolated instance for peaches on a black earth in Tasmania.

Baxter (1957) records iron and zinc as the most common trace element deficiencies on the brown solonized soils of the irrigated areas of Victoria. Here the chlorosis is aggravated where irrigation water is high in bicarbonate. Chelated iron compounds have proved expensive and unsatisfactory on these very alkaline soils and the recommended treatment is the insertion of gelatine capsules, filled with iron citrate, into holes drilled in the trunk. The features of an affected soil, the Barmera sandy loam, are given as follows:

Depth in inches	pH	Per cent $CaCO_3$
0–6	8.8	9.5
6–12	8.9	18.9
12–18	9.0	24.1
18–24	8.7	22.4

A second severely affected soil described by Baxter is a gray soil of heavy texture. The surface soil is a friable calcareous clay loam and the profile has reaction values between pH 8.6 and 8.8 in the top 24 inches. (See description of similar soil by Blackburn *et al.* (1953) in Section VII, C.) The records of deficiencies on pineapples and fruit and vine crops in Queensland and on oats in Western Australia are on acid soils, krasnozems, red earths, podzolic soils, and peaty sands, and in part have been linked to chlorosis due to excess manganese. For example, according to Fergus (1954) pineapples grown on the acid Dagun soil, a krasnozem in southern Queensland, on which manganese toxicity of dwarf beans is common, must be sprayed with iron sulfate as often as 10 times a year to control chlorosis. The Dagun profile consists of up to 10 inches of dark reddish-brown friable clay loam of crumb structure, pH 6, over 10 to 16 inches of red-brown friable clay; this overlies about 18 inches of red-brown firm massive clay resting on a yellow-brown and red-brown mottled C horizon of clay and decomposed rock derived from manganiferous jasper interbedded with slates and shales. The reaction of the surface soil is reduced to as low as pH 4.2 where ammonium sulfate is used as a fertilizer on pineapples.

VIII. Conclusion

A. Economic and Agricultural Significance

The agricultural economy of Australia is heavily dependent on the use of fertilizers. Superphosphate contributed greatly to the restoration of a declining arable agriculture in the early years of the century and has subsequently given a severalfold pasture production over great areas. In this latter role, superphosphate has not played a solitary part. Legumes have been vital for the provision of nitrogen, and trace element fertilizers have commonly been indispensable for pasture establishment. Millions of acres of worthless land, some of it indeed long known as desert despite a moderate rainfall, have been made productive and have expanded our agricultural resources to a remarkable degree. We quoted earlier Thorp's observation that reweathered soils, new soils for old, are poor indeed. There is, however, a growing confidence that wherever the climate is satisfactory, leached soils can be converted by man to virtually new and altogether more fertile soils. There has been a gain not only in current production but in the long-term agricultural prospects.

In addition many long known, obscure and costly ailments of plants and livestock have been remedied.

B. Future Outlook

All this is encouraging progress, but many problems remain. Australia is seriously lacking in fertilizer resources. It has no commercially useful deposits of phosphate, potassium, or elemental sulfur. For the time being nearby Pacific island deposits are meeting our phosphorus needs, but in half a century or so Australia must look to more distant sources. The readiness with which potassium is depleted on many of our soils foreshadows a steadily growing need for potassic fertilizers, which must all be imported. Steps have already been taken to develop pyrites as a source of sulfur for acid in superphosphate manufacture. These are economic problems of fertilizer supply which emphasize the need to avoid any waste in our use of fertilizers such as now occurs with phosphates on many European soils.

On the technical side we still have but a hazy picture of the future of the monsoonal north. Agriculture, and pasture improvement, have made little progress, principally because of the difficulties of plant production in a short monsoonal season. Experience of fertilizer requirements on these soils is fragmentary, but the morphology and genetic history of the soils clearly indicate that we may expect a repetition of southern Australian experience with deficiencies both of phosphorus and the trace elements.

In arid areas our information is even more scanty but again the pedological history suggests that where irrigation is possible fertilizers will have a prominent role.

In areas already being raised in fertility, many problems of land use are yet to be solved. All too commonly the viewpoint of the landholder who is using leguminous pastures to improve his production is that his developmental task is complete, that he has established a permanent pattern of land use. But this is unlikely. Rising fertility is creating new and unexpected weed problems, pastures are often not as good as in former years. These pasture regions must look to the exploitation of the new levels of fertility especially of nitrogen by cropping; in a few instances this is already occurring, with excellent yields of cereals and root crops. Just as pastures have assumed their place in cropping regions, so are we likely to be faced with the task of finding a versatile agriculture for the pasture areas emerging from scrublands.

To the research worker, the most notable feature of the progress in fertilizer use has been that practice has outstripped the understanding of the factors governing nutrient availability in soils. The need to press forward in this sphere is based not only on its scientific importance but on the many examples already before us of secondary consequences of fertilizer use, such as lime-induced deficiencies, the phosphorus-zinc intraction, the influence of fertilizer practice on molybdenum and magnesium availability and so on. It is to be hoped that the progress in fertilizer use will serve as a stimulus to the fuller understanding of the behavior of the nutrient elements both in the soil and in the plant.

Acknowledgments

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Appendix

Profiles Described in the Text

(See also general descriptions of the Great Soil Groups in Section III, C)

Calcareous aeolian sands	
Robe calcareous sand	VII, A and B
Currie calcareous sand	VII, A
Acid swamp soils	
Njookenboro peat	VI, D
Unnamed soil	VII, A
Podzols and ground-water podzols	
Plantagenet peaty sand	VII, A
Lucaston sand	VII, F
Lateritic podzolic soils	
Mungite sandy loam	VI, A
Kojonup gravelly sand	VI, B
Kuitpo gravelly sandy loam	VII, D
Meadow podzolic soils	
Kalangadoo sand	V, B
Unnamed low humic gley	VI, A
Frodsley sandy loam	VI, A
Riddoch sand	VI, D
Other podzolic soils	
Grainger sandy loam	VI, C
Unnamed soil	VI, D
Whakea sand	VII, A
Mt. Burr sand	VII, C
Gowangardie loam	VII, D
Unnamed soils	VII, E
Krasnozems	
Unnamed soil	VI, A
Unnamed soil	VI, B
Unnamed soil	VI, C
Unnamed soil	VII, D

Dagun clay-loam	VII, G
Black-earths	
Unnamed soil	VI, B
Rendzinas	
Millicent clay	VII, E
Fen soil	
Badenoch friable peat	VII, A
Solodized solonetz	
Laffer sand	VII, A
Solonized brown soils	
Winkie sand	VII, C
Barmera sandy loam	VII, G
Red-brown earth	
Urrbrae loam	V, B
Gray and brown soils of heavy texture	
Cununurra clay	V, B
Unnamed soil	VII, C
Unnamed soil	VII, G
Calcareous lateritic soil	
Tinkurrin sand	VII, E

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CASTORBEANS: A NEW OIL CROP FOR MECHANIZED PRODUCTION

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I. Introduction

Since antiquity the castorbean plant, *Ricinus communis* L., has been of utilitarian and ornamental value to man. It is considered by some to have been the "gourd" that played a decisive role in solving one of Jonah's predicaments. Even before Biblical times, man had found that the plant produced seeds with a useful oil. The sarcophagi of the ancient Egyptians contained castorbean seeds, and the utility of the plant was recorded in the earliest writings of the Hindus (Daugherty, 1904).

The Romans saw a resemblance between the seed and the insect commonly called the "tick"; they called both "Ricinus" (Nichols, 1911). The word "castor" was coined by English planters and traders—from *agno casto,* the name used for Ricinus by the Portuguese and Spaniards in Jamaica, where it was widely grown during the eighteenth century (De Candolle, 1890).

By the middle of the nineteenth century there were 23 castor oil mills in the United States. Earlier production may possibly have been greater, but the crop has never been of more than minor importance (Weibel, 1948). Domestic production was usually near the mills, which were generally located on the northern fringe of the cotton belt. By 1870, Weibel reports, only six castor oil mills remained in operation; three in Texas and one each in Missouri, Tennessee, and New Jersey. The last mill was located conveniently for crushing castorbeans that had been imported. This practice was apparently more economical than crushing domestically produced castorbeans, for domestic production had declined to practically nothing by 1900.

Nevertheless, consumption of castorbeans in the United States has risen sharply in this century. Between 1900 and 1940 it rose from about 13,000 tons to more than 100,000 tons (over 20 per cent of world production). World production of seed has ranged between 474,000 and 571,000 tons (currently about 540,000 tons) during the past fifteen years. About 60 per cent is produced in Brazil and India; Africa, Mexico, and Italy are other important producers. According to the United States Department

of Commerce,[1] the trend of world consumption of castor oil has been gradually upward since 1945; by 1961 it should be about 565,000,000 lb. (from about 565,000 tons of seed). Consumption of oil in the United States has been stable over the past ten years, at about 120,000,000 lb. The supply available to this country may be affected by new demands abroad [1] resulting from a new development in the production of plastics and synthetic fibers (Aelion, 1956). Within the next few years, Europe and South America, where the new industry is being developed, may annually need an additional 37,000,000 lb. of oil.

A modern use of castor oil is in the production of sebacic acid, involved in manufacturing certain plastics, nylon bristle, and synthetic lubricants for jet aircraft. Other uses are in manufacturing all-purpose greases, hydraulic fluids, artificial leather, pharmaceuticals, soap, printing ink, special low-temperature lubricants and flexible coatings, and fast drying oils for paints and varnishes. As these examples attest, castor oil is one of the more versatile of the vegetable oils, capable of several kinds of chemical transformations. Additional information can be found in Eckey (1954). Many more useful derivatives have been developed. A private company lists more than 175.

With the development of many new uses for castor oil, and with little assurance of a stable supply of seed or oil from foreign sources, interest has been renewed in the production of castorbeans in the United States. Even before the development of the newest uses for castor oil, interest in domestic production was stimulated by war needs. During World War I, castor oil was used as a lubricant for airplane engines. Domestic production was attempted to forestall the possibility of a shortage. At that time, culture of castorbeans was in a comparatively primitive state. Harvest of the crop required much hand labor, because of the dehiscence of the seed, and the attempt of domestic production failed. Research work on the problem, begun during the war, was abandoned with the war's end. Thus, no material progress in culture of the crop had been made when World War II began. Attempts at domestic production during this war were also unsuccessful, although research on castorbeans was resumed.

Research was continued after World War II, because many new uses had been found for the oil. In addition, some important contributions had been made to the culture of the crop. Indehiscent varieties made a single harvest possible, replacing the several harvests previously required, these indehiscent varieties were made usable by a mechanical huller that removed the pericarp of the three-seeded capsule (Gordon, 1943; Arnold and Sharp, 1944; Reed and Brown, 1944). Since World War II, farmers as well as public and private research agencies have advanced the culture of

[1] Publ No BD-57-95. U S. Dept. Commerce, Washington, D.C., 1957.

castorbeans to a point where it begins to approach that of an established crop. Plant breeders have developed inbred lines that make F_1 hybrids available for the commercial crop. Dwarf varieties with short internodes are available in the high plains of Texas, where loss of seed from strong winds is a problem. By 1955, engineers (Schoenleber *et al.*, 1957; Coppock and Schoenleber, 1957) had developed a mechanical harvester that gathered and hulled the seed in one operation. This development was generally considered "the break-through" to domestic production in the United States. If machines of this kind had been available during the Korean War, while the United States government had a procurement program, domestic production might have been maintained after the war ended. Instead it declined 95 per cent, from over 100,000 acres to less than 5,000 acres. About 15,000 acres of castorbeans were grown in the United States during 1957 (see Figs. 1 and 2).

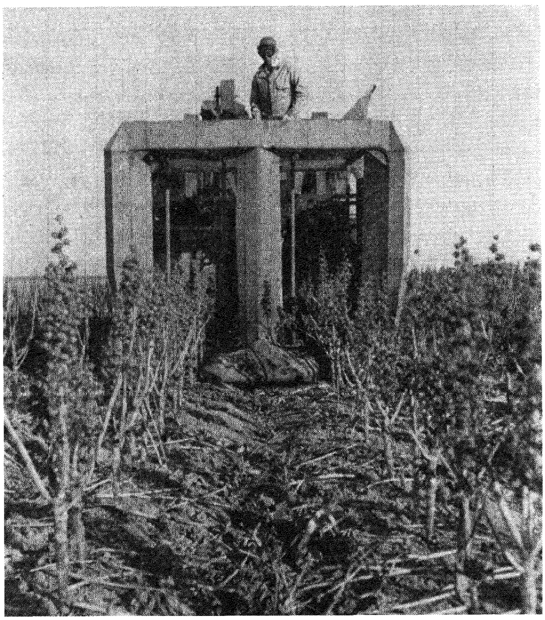

FIG. 1. Harvesting dwarf-internode castors, 3 feet tall, on the Texas High Plains, 1956. (Courtesy L. G. Schoenleber, U.S. Dept. Agr.)

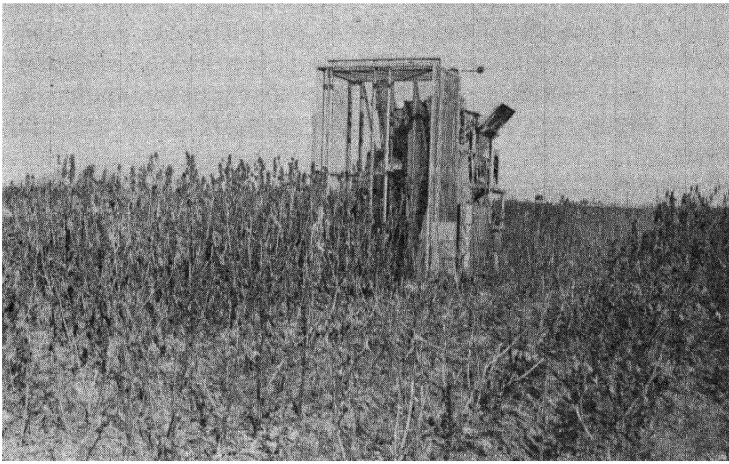

FIG. 2. Harvesting normal-internode castors, 6 feet tall, in the lower San Joaquin Valley of California, 1956. (Courtesy L. G. Schoenleber, U.S. Dept. Agr.)

II. Botany and Genetics

A. BOTANICAL DESCRIPTION

Ricinus, a monotypic genus, belongs to the Euphorbiaciae, or Spurge, family. Different species have been described, although no real crossing barriers have been detected among the so-called species. *Ricinus communis* L. is generally considered to include all of the many polymorphic types. It is believed to have originated in Abyssinia. No near relatives of the castorbean plant are known. Richharia (1937) proposed that the castorbean plant may be a polyploid, with a basic chromosome number of 5, the 1 n number being 10. Thus castors may owe their origin to polyploidization. Castors are distributed throughout the tropics and subtropics, where they are occasionally aggressive weeds. They are well known throughout the southern half of the United States, where they are often grown around dooryards. In Florida and southern California, castors have escaped and grow wild along roadsides and in washes.

1. Description of the Plant

The castorbean plant is a potential tree. It grows as a perennial in the subtropics and tropics, where it may attain heights of 30 to 40 feet. In

temperate zones it behaves like an annual, its growth being terminated by frost. The present commercial types, depending on environment and variety, may vary in height from 3 to 12 feet or more. Soil conditions may create a great deal of height variation within varieties. Castors have a tap root system, with prominent lateral roots a few inches below the soil surface.

The leaves, palmately lobed, are borne more or less alternately on the stems, except for two opposite leaves at the node just above the two cotyledonary leaves. The petioles are usually several times as long as the long axis of the leaves. The main stem is terminated by a raceme, known as the first or primary raceme, usually the largest on the plant. The primary raceme of domestic varieties in the United States usually occurs after the sixth to twelfth node. In wild types it may occur after seventy or more nodes. After appearance of the first raceme, branches to the main stem originate at the nodes. The number of branches depends on plant spacing and, in some cases, on the variety. Under field conditions, two or three shoots occur almost at the same time, but generally in the following order: the first at the node just beneath the first raceme, the second at the second node, and the third at the third node. Each of these shoots is terminated by a raceme, usually after four or five nodes have formed. These racemes are sometimes collectively called the second set. Subsequent shoots arise from the first node just beneath each of the racemes of the second set. Depending on environment, additional shoots may arise at each or any one or more of the second nodes, just as in the case of shoot development below the first raceme. This sequence of development of stems and racemes continues as long as the plant lives. The development of racemes along any one axis is sequential, making it possible for a plant to have racemes in all stages of development, from bud stage to complete maturity (Fig. 3). Hilpert (1941) has described a shoot development below the first raceme that differs from that described here: the shoots on the main stem originate at basal nodes rather than at the nodes just below the first raceme; then development is in the normal manner.

The castor plant is usually monoecious, with the racemes bearing female flowers on the upper 30 to 50 per cent and male flowers on the lower 70 to 50 per cent of the raceme. The number of flowers and the proportion of male to female can vary greatly, as described in Section II, B4. The flowers, both male and female, are apetalous, each being enclosed in a fused calyx and borne on a small pedicel. The bud of the male flower is flattened conically and the calyx surrounds a cluster of many stamens with branched filaments. The male flowers are generally pale yellow at anthesis. The female flowers are conical and more slender than the male

flowers. The calyx of the female flower encloses a pistil with a three-carpelate ovary and sessile stigmas. Each carpel has one ovule. The stigmas ordinarily are reddish at anthesis. Both the male and female flowers occur in clusters of three or more, arising spirally on the raceme axis. Thus the inflorescence is actually a branched raceme or panicle. Self-pruning of the flowers under certain environmental conditions may give the inflorescence in varieties with very short pedicels the appearance of a simple raceme or of a spike.

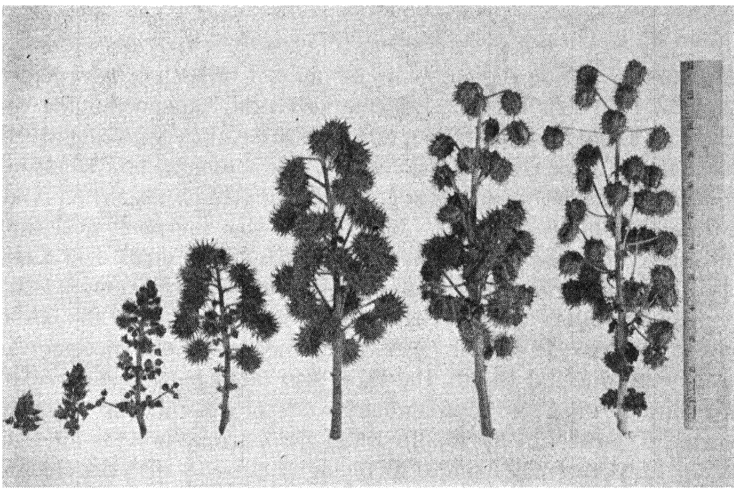

FIG. 3. Normal monoecious racemes taken on the same day from one plant showing range of development from before anthesis to complete maturity.

The male flowers dry up and usually drop off after the pollen is shed. The pollen is carried to the stigmas mainly by wind. After fertilization, the female flowers develop into capsules that are spiny, though spineless variants are common. The hull or pericarp of the capsule may split violently along the dorsal suture of each of the three carpels at maturity. This type of dehiscence is not characteristic of the commercial varieties now grown for mechanized production.

As mentioned previously, each carpel produces one seed. The seed may vary greatly in size, from 450 to over 5000 per pound, depending on variety and environment. The seeds of current commercial varieties range from about 1400 to 1800 per pound. Seed shape may be obovoid to oblong to almost round, all with an arched dorsal surface and a nearly flat ventral surface having a prominent caruncle. Seed color may be white, gray,

brownish-yellow, brown, black, or various shades of red. The ground color is usually modified by one of several mottling patterns. The outer pattern color may be gray or brown to black. The pattern may vary from fine-veined to coarse-veined, or from fine dots to large splotches. The seed coat makes up about 25 per cent of the weight of the seed of current commercial varieties. The remainder is mostly endosperm with embedded embryo, which consists of two thin cotyledons, a shoot and a radicle, all plainly visible upon dissection of the seed. The seed, depending on variety and environment, contains 40 to 57 per cent oil.

2. *Cytology*

The first report on the chromosome number of Ricinus was made by Nemec, in 1910 (Taylor, 1926). He reported the haploid number to be 10 and the diploid number being 20. This observation was confirmed by Sussenguth (Taylor, 1926). The root tip chromosomes of Ricinus were described by Taylor as small, slightly tapering rods, usually curved in the equatorial plate. Lewitsky (1931) found that morphological studies of Ricinus chromosomes were made difficult by their small size. A shaft-shaped attenuation with a sometimes perceptible head of only 0.1 to 0.2 microns, he reported, is very characteristic for a number of the chromosomes in Ricinus. He further noted that many of the chromosomes have arms of very unequal length, the short arm often being separated by a sharp constriction. From a preliminary study of a number of varieties of castorbeans, Jacob (1956), reported that Ricinus may provide interesting material for cytogenetic studies involving pachytene analysis. He found that the machrochromomere pattern of the chromatic zone is apparently distinct in each of the ten chromosome pairs at pachytene. He also found that all centromere regions identified were median or submedian.

Richharia (1937) reported on meiosis of Ricinus and on a correlation between genetic segregation and secondary associations of chromosomes. Ten bivalents were observed to form regularly. No nucleolus was detected. Secondary associations were noted to be common at the first and second metaphases. He therefore suggested that the castorbean plant appears to be a secondarily balanced polyploid. Based on the work of White (1918), Harland (1928), and Peat (1928), Richharia presented genetic evidence to support polyploidy in Ricinus. He pointed out that the color of the vegetative parts depends on the presence of three independent gene pairs, and that the various types of leaf bloom (waxy substance) depend on three separate gene pairs. Evidence of complementary genes for seed-coat pattern further supported his argument for polyploidy in Ricinus. Secondary association in castors has also been observed by Kurita (1946).

B. Inheritance of Characters

Genetic studies on castorbeans have not been extensive. The first inheritance studies, by White (1918), Harland (1920, 1922), and Peat (1928), were on leaf and stem color, bloom and its distribution, spines on the capsules, color and pattern of the seed coat, leaf shape, and albinism. These studies were reviewed by Harland (1928). Subsequent studies are reviewed here.

1. Bloom

This character is expressed by a white, waxy substance on both the vegetative and reproductive parts of the plant. The presence or absence of bloom has been reported as due to a single gene, *B-b*, with bloom partially dominant over no bloom; however, Zimmerman (1957a) later established that expression of bloom is due to two complementary genes. In addition, various modifiers of bloom character intensify its expression on various plant parts. Besides the three classes of bloom described by Patwardhan (1931), five more classes concerned with intensity of bloom have been described by Narain (1952). The inheritance of these classes has not yet been reported.

It is not known whether bloom character is economically significant. Harland (1947), in a study of frequency of the *B-b* gene pair at different elevations in Peru, found that the proportion of plants with bloom increased with increase in sunlight and diminution of fog. In warmer areas (Phoenix, Arizona, for example) varieties without bloom are observed to be generally not as productive as those with bloom. At Davis, California, where it is not as warm, this difference has not been observed. It appears, then, that bloom may have economic significance if climate is warm enough. Breeding work is under way to develop near-isogenic lines, which will enable a more precise evaluation of the bloom character.

2. Number of Nodes to First Inflorescence

This character, of some significance as indicating time of initiation of the first inflorescence, is used to describe varieties as to their maturity. The relationship was shown by Domingo (1945a). He found that frequency curves for date of first flowering were very similar to those for number of nodes to the first inflorescence, with the latter curves slightly smoother.

There is wide variation in node number of the first inflorescence. Where the plant is an annual with a growing season of about 200 days, the number of nodes to the first inflorescence in a segregating population may vary from 6 to 45 and some segregates with a slightly higher node number may be flowerless. Domingo (1945a) reported on the inheritance of node

number to first raceme and on the flowerless condition accompanying some of the highest numbers. From certain crosses in F_2, he obtained flowerless plants along with plants that flowered at higher node numbers than either parent, the mode of inheritance being polygenic. The F_1 populations contained no flowerless plants; the mean for node number generally fell midway between the parents. Domingo found a distinct bimodal frequency distribution that gave a good fit of 3:1 ratio in an F_2 population having no flowerless plants and a distribution within the range of the parents, suggesting that one major gene pair governed earliness in the material studied. Zimmerman (unpublished data, 1952) obtained evidence indicating that two gene pairs are responsible for earliness, either pair producing earliness in the material studied. A very distinct bimodal distribution was obtained in F_2 plants, with 199 having node numbers of 4 to 8 to first inflorescence, about the range of the parents, while 16 plants had numbers of 12 to 18. This gives a good fit to a 15:1 ratio. The parents carried different genes for earliness and a double recessive was necessary to produce the late-flowering plants. Late-flowering or high-node types may not occur until several generations after increase from the breeder's seed. In light of the genetic data and field observations, it would seem that there are several to many genes that condition the time of initiation of the first inflorescence.

Domingo (1945a) pointed out that the flower regulating mechanism is probably influenced by one or more environmental conditions, since day length, light intensity, and temperature levels change throughout the growing season. An effect of date of planting on node number to first inflorescene was shown by Peat (1928). With three samples of F_2 population planted at monthly intervals in Trinidad he found that the node number of the last planting was significantly different from that of the first two plantings. Regional variety trials in the United States with plantings on different dates at a single location have given node number that agree with Peat's data. However, not all varieties behaved similarly. Some varieties are very little affected by date of planting, while the mean node number of others may change from 8 to 16.

3. *Plant Height*

Castorbean height is naturally related to length of internodes and number of internodes. Inheritance studies of internode length are difficult because internode length is greatly modified by such environmental conditions as soil fertility, moisture, and temperature. The dwarf-internode type described by Krug (1945) is distinguished by short internodes and by nodes that are sinuous (instead of encircling the stem in one plane as in normal-internode plants). Zimmerman (1955, 1957b) reported on

the inheritance of dwarf-internode character and its association with several agronomic characters. He found that it was controlled by one recessive-gene pair and was inherited independently of node number of first raceme, total number of nodes, dehiscence of the capsule, and monoecious or pistillate nature of racemes. Zimmerman (unpublished data, 1955) found that the dwarf-internode character and the interspersed character are inherited independently (see Section II, B4b). He found linkage between dwarf internode and spiny capsule with a recombination value of 0.17–0.07 (unpublished data, 1955). In a comparison between normal- and dwarf-internode F_2 segregates for average internode length below the first raceme and for first-raceme length, these characters in dwarf-internode segregates were found to average 54 and 84 per cent, respectively, of the same characters in normal-internode segregates (Zimmerman, unpublished data, 1955). Length of raceme axis is also influenced by the dwarf-internode gene, but not as much as is the main stem.

4. *Sex*

The normal monoecious raceme has pistillate flowers on the upper 30 to 50 per cent of the raceme, and staminate flowers on the lower 50 to 70 per cent. Variations in amount and distribution can be extreme, including: (1) racemes with 99 per cent pistillate flowers to nearly zero per cent; (2) racemes with nothing but pistillate flowers along their entire length; (3) racemes with various proportions of pistillate and staminate flowers interspersed along their entire length; and (4) a variation from flowers of separate sexes to a few hermaphroditic flowers.

Plants have been observed that have all or any combination of the four types of raceme variations mentioned. When these different types of racemes occur on the same plant, progressive development is from a higher percentage of pistillateness to a lower percentage; the reverse order has not been reported. Thus pistillate expression is greatest in the earliest racemes, especially the primary one.

Environment has a strong influence on sex expression. Shifriss (1956) reported that female tendency may increase most conspicuously after severe pruning of well-established plants. Female expression is enhanced by moderate temperature and optimum soil fertility and moisture; male expression is enhanced by high temperature and low soil fertility and moisture. Under perennial culture, male tendency may also be increased by fairly low temperatures (Shifriss, 1956). As one would expect, expression of sex is influenced by the seasons. Female expression is greatest in spring and early summer, male expression in late summer and early fall.

a. Pistillate Variants. According to Shifriss (1956), Roxburgh (1874) discovered a female castor plant that led him to believe that dioecious

species exist in the genus. Katayama (1948), in reporting on the inheritance of sex in gynodioecious strains, suggested that gene *a* determines the female condition and gene *A* the normal monoecious. Claassen and Hoffman (1950) suggested a similar genetic mechanism for determining the female and normal monoecious condition. One culture on which they reported, now known as Nebraska 145-4, proved very stable in sex expression: progenies produced by sibbing pistillate plants with heterozygous monoecious plants had 1:1 ratios of these sex types, with only occasional reversion. This stability has since been confirmed by other workers. Zimmerman (unpublished data, 1957) has been able to maintain a fair intensity of expression of the N-145-4 pistillate gene through four backcrosses using CIMARRON as the recurrent parent. Shifriss (1956) proposed the symbols *F-f* for the locus concerned in the Nebraska 145-4 type of sex expression. He found a linkage between some of the polygenes that control number of nodes to the primary raceme and the *F-f* locus.

Shifriss (1956), in an extensive search for spontaneously occurring pistillate plants found their incidence to range from 1:375 to 1:16,400 in different castor populations. He was able to study their development and inheritance under a perennial growth habit. Not finding a single genetically stable female mutant, he concluded that a stable variant of the Nebraska 145-4 type must be extremely rare in nature, an opinion generally shared by other workers. He chose to call the unstable mutants "sex reversals." According to him there are several types of sex reversals, with classification based on the stage of development at which reversion to monoecious takes place. Reversion was observed to occur on racemes subsequent to the primary or after the plant had produced over 500 pistillate inflorescences. When the pistillate racemes of sex-reversal plants are crossed with genetically stable races, the sex reversals in F_1 range from 0 to 100 per cent; crosses with late-reverting sex reversals gave the higher percentages. Reciprocal crosses showed sex reversal to be under nuclear control.

Shifriss (1956) performed several breeding experiments to study the nature of sex reversion in sex reversals. Pistillate racemes and emasculated monoecious racemes on the same sex-reversal plants were crossed with a normal monoecious variety. The F_1 from pistillate racemes produced an average 30.3 per cent of sex reversals, while that from emasculated racemes produced 2.7 per cent sex reversals. This difference in the F_1 generation suggests that reversion from femaleness to monoecism is associated with a corresponding hereditary change. However, Shifriss pointed out that if a hereditary change is assumed one cannot account for the 100 per cent sex reversals that often occur in the immediate progeny from selfed, late-reverted females. In another breeding experiment on the nature of sex

reversion, Shifriss selfed and reciprocally crossed monoecious racemes of late-reverted sex reversals with a stable "female" line of Nebraska that bears a few staminate flowers at the base of the racemes. The F_1 produced 14 per cent sex reversals; the selfed progeny produced 75 per cent, in contrast with the expected 26 per cent. Since crossing early-appearing pistillate racemes of late-reverted females often results in close to 100 per cent sex reversals in the F_1 generation, the deviation from the expected is not explained by lower penetrance in the F_1 than in the progeny obtained from selfing. To account for sex instability, Shifriss proposed a tentative genetic hypothesis involving a nuclear factor that mutates into different supressors varying in degrees of supression and stability, the mutations being reversible. The supressor acts on *F*, the gene for normal monoecious and the degree of supression depends on the kind and the dose of the supressor, the potential sex tendency of *F*, and the non-genetic variations.

b. Interspersed Male and Female Flowers. Interspersed lines or varieties have racemes with various proportions of pistillate and staminate flowers interspersed along their entire length. For convenience of classification, such distribution of staminate and pistillate flowers is referred to as 100 per cent pistillate and 100 per cent staminate along the raceme.

The proportion of male flowers to female is influenced considerably by environment. For example, the variety U.S. 3/415-9 is clearly an interspersed type when grown in the summer at Davis, California; but grown in the winter in Florida, it appears to be almost pistillate, having very few male flowers.

Inheritance of the interspersed character is of special interest since it is involved in the production of commercial F_1 hybrids. F_1 progenies of female N-145-4 plants crossed with interspersed lines are pistillate (Zimmerman and Parkey, 1954). Thus 100 per cent staminate distribution appears to be recessive. Zimmerman (unpublished work, 1953–1957) has studied the inheritance of interspersed character in crosses with varieties that have normal monoecious racemes, i.e., only pistillate flowers on the upper part of the raceme and only male flowers below. He found that the 100 per cent pistillate distribution of the interspersed varieties tended to be dominant over the normal monoecious type of sex distribution. However, F_1 progenies of the interspersed U.S. 49 crossed with normal monoecious varieties segregated for both parental raceme types, both between and within plants. The interspersed variety U.S. 3/415-9, however, seemed to carry a greater prepotency than did U.S. 49 for transmission of its 100 per cent pistillate distribution. Of 947 F_1 plants from reciprocal crosses involving U.S. 3/415-9, all but 3 had 100 per cent pistillate distribution on the first raceme, and all but 9 had 100 per cent pistillate distribution on all racemes (Zimmerman, unpublished data, 1957). However, the instability

of the interspersed character of U.S. 3/415-9 was expressed in the segregating F_2 and test-cross populations. Based on the first racemes of progenies from single plants of the same F_1 generation, the ratios of 100 per cent pistillate distribution to normal monoecious distribution ranged from 63:1 to 1:3. Similarly, the test-cross progenies had ratios ranging from 7:1 to 1:7. Thus it appears that U.S. 3/415-9 contains a factor or factors for expression of the 100 per cent pistillate distribution that are stable in the genic background of U.S. 3/415-9 and almost as stable in the genic background of an F_1 but unstable in a segregating population. In U.S. 49 the factor or factors for expression of 100 per cent pistillate distribution show stability only its own genic background. The interspersed varieties apparently show a range of instability for sex somewhat like the sex reversals described by Shifriss.

Sex distribution on racemes in segregates from interspersed × normal monoecious lines has been observed to fall into six classes: (1) normal monoecious; (2) all pistillate; (3) male and female interspersed; (4) normal monoecious interspersed with male; (5) a few hermaphroditic flowers along with flowers of single sex; and (6) nearly all staminate flowers.

5. *Resistance to Disease*

There is a report of the inheritance of resistance to only one of the many diseases that affect castorbeans, namely bacterial leaf spot, *Xanthomonas ricinicola*. Poole (1957) found resistance to this disease to be determined by one major recessive gene pair, which he denoted as xx. He also found that two minor genes, x_1 and x_2, work additively to intensify resistance. He reported that CIMARRON carries three gene pairs for resistance, xx, x_1x_1, x_2x_2, and that any segregates from crosses involving CIMARRON that contain xx would possess field resistance to bacterial leaf spot.

6. *Capsule Dehiscence*

White (1918) found capsule dehiscence to be influenced by two dominant genes, one concerned with thick, leathery pericarp and the other with capsule opening. F_2 progenies from crosses of dehiscent thick, leathery capsules × indehiscent brittle, thin-walled capsules segregated in a 9:7 ratio. The genes for capsule dehiscence were dominant in all F_1 progenies. White's findings have been generally substantiated by other workers, although there are probably more than two dominant genes involved in dehiscence (Parkey, unpublished data; 1953).

The complicated nature of capsule dehiscence was shown by Hocker (1956). From comparative histological studies of dehiscent and indehiscent varieties, Hocker concluded that the basic cause of dehiscence

includes several agents: (1) an asymmetry of structural pattern in the endocarp; (2) the action of hydrolytic enzymelike substances in the locule suture; and (3) sufficient moisture to allow the first two agents to operate. Hocker also pointed out that soil and climatic conditions influence dehiscence. His findings are in agreement with field observations, i.e., the considerable effect of location and season on dehiscence.

7. *Oil Percentage*

Oil percentages ranging from 42 to 58 per cent in a series of castorbean varieties have been reported by Popova (1926), Van Horn and Zimmerman (1955), and Poole (unpublished work, 1955). The wide range appears to indicate that oil percentage is controlled by multiple factors. Little or no work has been reported on the inheritance of oil percentage. Zimmerman (unpublished work, 1953–56) found that Nebraska 145-4 as a female parent tended to exert a dominant influence on the oil percentage of F_1 hybrids. This was also observed by Poole (unpublished work, 1955). However, N-145-4 is considered to be a high-oil variety at Zimmerman's location, but not at Poole's. This is not unusual since genotypic rather than phenotypic relationships are involved. Zimmerman (unpublished work, 1955) observed complete dominance for high oil in the F_1 from a wide cross involving breeding lines 3/384-8-6 and 4/328-21, with oil percentages of 57 and 46 per cent, respectively. One cannot be certain, however, whether dominance was responsible instead of physiological response induced by heterosis.

Percentage of oil is associated with several other seed characters. Domingo (1945b) showed a highly significant positive correlation of 0.568 between oil percentage and test weight. However, lines with similar test weights often had different oil percentages. Per cent of kernel of the seed has also been shown to be positively correlated with oil content. Where range of seed size is large, per cent of kernel is more closely correlated with oil content than is test weight.

III. Breeding

A. Objectives

The ultimate objective is high yield of oil per acre since castorbeans are grown for the oil in the seed. However, characters that facilitate mechanical harvesting are important objectives in castorbean breeding because of the importance of mechanical harvest to commercial production in the United States.

Indehiscence of the capsule, resistance to capsule dropping, short

plant height, a minimum of basal branches, and sufficient height of first raceme are all desired for machine harvest. Varieties with most of these characters have been developed and are in commercial production. Yet a wide variability in the characters important to mechanical harvesting still persists in most of the breeding material. The breeder working with any one of them or with other characters is generally confronted with the problem of maintaining or incorporating desirable characters at levels already achieved, or better.

B. Techniques

The castorbean plant reproduces both by self- and by cross-pollination. Domingo (1944) reported 36 per cent out-crossing. Meinders and Jones (1950) found that pollen contamination may result even when castors are isolated by as much as 60 rods. Thus, controlled pollination is necessary in a breeding program.

Self-pollination is effected by enclosing the raceme in a bag of parchment or Kraft paper. In enclosing the young raceme in a 4- x 15-inch bag, two or more leaves and axillary buds are removed so the bag can be fastended to a stronger part of the stem. A difficulty encountered in selfing castorbeans is enclosing the raceme in a bag large enough to protect it throughout the period of anthesis, when raceme length may grow from under 2 inches to 24 inches or more. A change to a larger bag is sometimes necessary.

The bags may be worked like a bellows when pollen is shedding to ensure maximum pollination, since the male flowers are located below the female flowers. If relative humidity is high, the bag must be removed during capsule development to prevent molds from overunning the raceme.

Emasculation is easily effected by rubbing off the male flowers on the lower part of the raceme. The emasculated raceme is protected by a bag until pollination, usually about 10 days after emasculation. At Davis, California, pollen is obtained by collecting the desired male flowers in a small Kraft satchel-bottom bag. Bag and contents are set aside for 2 to 48 hours to permit the anthers to dehisce and to wait for periods of least air movement. The bag, usually closed during this period, is placed along with others in a paper box in the nursery. Only one or two minutes are needed to pollinate the stigmas on a raceme with a camel-hair brush. The raceme is then enclosed again in a paper bag, which is removed about 4 weeks later.

C. Methods

Inbreeding castorbeans seems to result in no detectable loss of vigor. Most of the inbred varieties in use today were developed by selection

within existing variability. The selections, selfed until practical homozygosity was obtained, were then evaluated as inbred varieties or, recently, in F_1 hybrid combinations. With the fixation of various characters in the breeding materials, the pedigree and backcross methods have come into use. Such simply-inherited characters as pistillateness of the N-145-4 type, dwarf internode, spineless capsule, stem color, and presence or absence of wax on the stem, are being transferred by the pedigree and/or the backcross methods. Long raceme, which is inherited quantitatively, has been transferred by the pedigree method. The interspersed male and female flowers character is also inherited quantitatively and has been transferred by a combination of the backcross and the pedigree methods. Resistance to bacterial leaf spot has been transferred by the pedigree method.

D. Hybrid Vigor

White (1918) observed F_1 castor hybrids that produced a larger amount of seed than either parent, together with F_1 hybrids that did not. In the light of these observations, he suggested a method of producing F_1 seed for commercial planting whereby the female parent was to be emasculated and pollen from the male parent applied with a pollen gun. Weibel and Woodworth (1946) suggested a similar method except for the use of a crossing block in which the emasculated racemes would be fertilized by wind pollination. Neither method has been used commercially. Claassen and Hoffman (1950) suggested using lines that segregate in a ratio of one pistillate plant to one heterozygous monoecious, the latter being rogued from the crossing block before flowering begins. The female plants would then be cross-pollinated with a selected pollinator line planted in every sixth to eighth row. This procedure is now being used commercially to produce single-cross hybrid seed, the female line Nebraska 145-4 or related material generally being used as one of the parents.

1. *Single-Cross Hybrids*

Zimmerman and Van Horn (1953) reported on yields of 22 single-cross hybrids in which N-145-4 was the female parent. The hybrids yielded 87 to 132 per cent as much as their respective higher-yielding parent. In a three-year period at Davis, California, a commercial hybrid, PACIFIC HYBRID 6, had a 14 per cent higher yield of seed than did the highest-yielding inbred varieties tested (Table I).

When three of the higher-yielding hybrids were compared with their parents at Davis, California, seed yield was 109 to 130 per cent of that of the respective higher-yielding parent (Table II). High oil content, high test weight, and high seed weight showed a tendency toward dominance.

TABLE I

Average Yield of Pacific Hybrid 6 and Highest-Yielding Inbred Variety in Tests at Davis, California

Year	Pounds of seed per acre	
	Pacific 6	Inbred variety
1954	3799	3342
1955	2969	2655
1956	3299	2870
Average	3356	2956

TABLE II

Yield and Other Agronomic Data of F_1 Hybrids in Per Cent of Their Highest Parent (Davis, California)

	N-145-4 × Cimarron			N-145-4 × U.S. 3/415-9		N-145-4 × N-224	
	1953	1955	1956	1955	1956	1955	1956
Seed yield	112[a]	120	109[a]	130[a]	113[a]	117	111[a]
Oil content	101	103	102	101	101	99	100
Test wt.	102	104[a]	101	99	97	102	101
Seed wt.	102	108[a]	109[a]	100	98	102	107[a]
Number of nodes to first raceme		67	67	85	73	100	100

[a] Significantly above higher parent.

Heterosis for seed yield, of course, can occur only as increase in seed number and/or seed weight. Inspection of the table shows that increase in seed number was the major factor in the heterosis for yield, although increase in seed weight contributed a major part two times out of seven. A tendency toward either dominance or no dominance for low node number to first raceme may contribute to increased seed number and weight. In crosses between lines with low and with high node number to first raceme, the hybrid will flower earlier than will the late or high-node-number parent and will thus start to produce and mature seed sooner. This applies in the hybrids of N-145-4 × CIMARRON and N-145-4 × U.S. 3/415-9. However, both parents of the N-145-4 × N-224 hybrid flower at the same node number. In this cross the male parent, N-224, yields about the same as N-145-4 but has smaller seed and lower test weight. Thus N-224 must produce a

greater number of seeds than N-145-4 in order to have a similar yield. Therefore the two characters seed weight and number entered the N-145-4 × N-224 cross in "repulsion phase," i.e., higher seed weight and lower seed number × lower seed weight and higher seed number. As pointed out, there seems to be dominance for high seed weight; this, along with dominance for high seed number, could account for some of the heterosis for yield in such crosses of "repulsion" type where the parents have a similar yield potential.

Some of the increase in seed number in certain crosses involves the sex mechanism. This is especially true of N-145-4 × U.S. 3/415-9, in which the F_1 is pistillate (see Section II, B, 4b).

It appears that heterosis for yield in castors may result from dominance or dominancelike effects involving such characters as node number to first raceme, seed weight and number when in "repulsion" phase, and sex distribution.

2. *Three-Way-Cross Hybrids*

As mentioned above, Nebraska 145-4 is used as a female parent in the production of single-cross hybrids. The procedure requires that the normal monoecious plants (of about 50 per cent frequency) be rogued prior to pollen shedding, thus allowing the female plants to be cross-pollinated with a selected pollinator that is planted about every sixth to eighth row. Several roguings are required to keep sib-pollination at a minimum. Zimmerman and Parkey (1954) suggested using three-way-cross hybrids (with a pistillate F_1 as the female parent) in order to eliminate roguing (II, B, 4b). Zimmerman (unpublished work, 1954–55) observed that the seed yields of two-way-cross and three-way-cross hybrids were not significantly different. However, the three-way-cross hybrids tended to produce a low frequency of giant plants, which are not suited to mechanized production.

IV. Production

A. Toxic and Allergenic Properties

Ricin and ricinine have been found to be the poisonous constituents of castorbean seeds. According to Funck (1942), these constituents comprise 2.8 to 3 per cent of the whole seed. Ordman (1955) reported that ricin, a protein, is extremely potent: a dose of 0.035 mg. may prove fatal to man; symptoms of poisoning may occur with a subcutaneous injection as small as 0.001 mg. per kilogram of body weight. He pointed out, however, that some people are able to eat the seed without ill effect, probably having in some manner acquired immunity. He also reported that cows

and fowl in the vicinity of an oil-processing factory in the Transvaal, South Africa, appeared to be unharmed by eating castor seed and hull debris. Ricin and ricinine have also been isolated from castorbean leaves, although the leaves have been reported to be nutritious cattle forage by workers in India. The foliage from young plants about 21 days old is considered to be more poisonous than that from older plants. The plant is generally observed to be unpalatable to livestock, for they do not eat it unless forced to by lack of other feed.

Castorbean seeds also contain a powerful allergenic substance, reported by Spies and Coulson (1943) to be about 1.8 per cent of the pomace (residue remaining after oil extraction). It is also present in the leaves (Woringer, 1944). The allergenic substance is separate and distinct from the toxic constituents, according to Ordman (1955). This is readily demonstrated in experimental animals. It is apparent from the evidence on these toxic and allergenic components that precautions are needed in producing castorbeans.

B. Domestic Acreage

After World War II, a private company needing a stable supply of castor oil initiated a domestic production program. By 1950, about 7,000 acres were devoted to castors, in Oklahoma, Texas, and California (Van Horn, 1952). The government encouraged domestic production of castors by means of a procurement program during the Korean War to avert possible shortage of castor oil. The incentive of a guaranteed price expanded production to about 63,000 acres in 1951 and to 125,000 in 1953. In 1954, because of a reduced guaranteed price, the acreage dropped to 27,000 (Table III). The next year, the procurement program was discontinued, and the acreage declined to 5,000.

Grower experience during the 1951–1955 period provided considerable information on adaptation of castorbeans. For example, California acreage (mostly in the Imperial Valley) dropped from 15,000 acres in 1951 to 1,300 acres in 1952. The available varieties were unable to tolerate some saline soils and high midsummer temperatures, and galelike winds ruined much of the crop. In addition, mechanical harvesting proved difficult, resulting in further seed losses. In 1953 California acreage increased to 3,700, mostly in the delta area of central California. The hybrid castors grown had been used semi-commercially in the delta area in 1952. Seed yields up to 3,000 lb. per acre demonstrated the adaptation of castors to this area, especially with subirrigation. However, mechanical harvesting difficulties resulted in field losses as high as 40 per cent.

An experimental castorbean harvester, developed by the Agricultural Research Service of the United States Department of Agriculture, was

TABLE III

Estimated Castorbean Acreage in the United States[a]

State	1951	1952	1953	1954	1955	1956	1957
	(thousands of acres)						
Tennessee	--	--	--	—	0 2	0.5	0 2
Mississippi	–	—	–	-	0.1	0 2	0.4
Arkansas	—	- -	1.3	1 0	0.2	0 2	0 1
Missouri	—	-	--	1.5	-	- -	--
Oklahoma	24 3	23.6	35.5	7.4	1 3	1 5	0.1
Texas[1]	19.5	72 2	79.6	10.0	—	0 5	2.9
Arizona (irrigated)	3.8	0.5	2.6	0.7	2 6	1.1	3.8
California (irrigated)	15.1	1 3	3 7	2 3	0.7	0.8	6.5
New Mexico (irrigated)	-	--	1 8	3.7	—		1.6
	62 7	97.6	124 5	26.6	5.1	4 8	15.5

[a] "The Fats and Oils Situation" FOS-188 U S Dept. Agr, Washington, D.C., January 1958

[1] 1951--1954 mostly dryland; since then largely irrigated.

successfully demonstrated in 1955. It encouraged production in the United States to 5,000 acres in 1956. The same year two types of commercial harvesters were built—one self-propelled, the other tractor-mounted—both using the harvesting principles of the U.S.D.A. machine. Acreage was tripled the next year, and even more would have been planted if sufficient harvesters had been available. About 13,000 of the 15,000 acres planted in 1957 were grown under irrigation, in Arizona, California, and the High Plains area of Texas and New Mexico. Most of the remaining acreage was in Mississippi and west Tennessee.

C. Adaptation

The three major factors pointed out by Domingo and Crooks (1945) as determining the areas of adaptation of castors—disease, length of growing season, and rainfall—generally hold true for current varieties. However, increased yields from hybrid varieties have extended the area of economic adaptation to irrigated areas.

1. *Diseases*

Thus far, diseases that affect castorbeans are a more serious problem in humid and high rainfall areas. *Sclerotinia ricini* Godfrey, or gray mold, eliminates much of the Gulf Coast region from the area of adaptation, as the disease is favored by high rainfall and humidity. In wet periods this fungus destroys the inflorescence at all stages of development. The only effective control is to plant mold-free seed in areas where climate does not

favor the disease, because no resistant strain is known (Domingo and Crooks, 1945).

Alternaria ricini (Yoshii) Hansford, or Alternaria blight, has been found on castorbeans throughout the United States, though less frequently in areas of low rainfall and humidity (Stevenson, 1945). Although it can attack the racemes in any stage of development, it most frequently attacks capsules that are about half size to full size. At the latter stage the fungus does relatively little damage to the seed. No known resistant varieties are available in the United States but some varieties are affected much less severely than others. The extent of losses from the disease in commercial production is not known. So far it appears to be negligible in the irrigated areas of the Texas High Plains, Arizona, and California. Considerable damage has been noted in nurseries at Gainsville, Florida, at Stoneville, Mississippi, and at Davis, California. Such capsule rots caused by Alternaria blight present a difficult problem; because the racemes do not mature as a unit, control by fungicides is limited. The best promise of control lies in disease tolerance or resistance, if either can be found, and proper selection of production areas.

Xanthomonas ricinicola (Elliott) Dawson, or bacterial leaf spot, has been reported in castors. It was quite extensive in Texas in 1953 (Poole, 1954). It usually occurs after periods of driving rains or heavy dews. In severe infections the organism may move down the petiole and into the stem. Other leaf-spot diseases, such as Alternaria and Cercospera, have been observed. They usually attack the lower, or older, leaves. The extent of their damage is not known. Resistance to bacterial and Alternaria leaf spot is evident in some varieties, markedly so in seedlings and, in several cases, the leaves of older plants.

Phymatotrichum omnivorum (Shear) Duggar, or cotton root rot, is known to attack castors (Taubenhaus and Ezekiel, 1936). Other diseases that evidently enter through the roots have also been observed. Damping-off organisms attack seedling castors, especially if the soil is too moist and the temperature is low. Protective seed treatment is recommended.

Castorbeans have been reported to be infected by numerous other diseases, including bacterial wilt, viruses (tobacco ringspot), scab, anthracnose, rust, and numerous leaf spots. More than 150 different organisms are known to be pathogenic on the plant (Thomas, 1953). Thus, with increased production of castors in the United States, more disease problems are to be expected.

2. *Growing Season*

Domingo and Crooks (1945) defined the region of adaptation to include areas that have growing seasons of 180 days or more. With present

varieties, satisfactory yields have been obtained in a growing period of 160 days. At Davis, California, test plot yields of well over 3,000 lb. per acre have been obtained in about 150 days.

3. *Moisture*

Domingo and Crooks (1945) stated that 15 to 20 inches of rainfall from April to September are essential to satisfactory yields. But, as already pointed out, irrigation extends the area of adaptation to the irrigated areas of New Mexico, Arizona, California, and the Texas High Plains. Two to 3½ acre-feet of water are required during the growing season.

Humidity must also be considered, from the standpoints of both disease and harvesting. High humidity favors the development of capsule molds, and relative humidity must be no higher than 45 per cent for current mechanical harvesters to remove and hull capsules efficiently.

4. *Soils*

Physical condition of the soil is important in castorbean production. It should have good drainage, with no compacted or impervious layers or claypans. It should have the ability to warm up quickly in the spring. Highly saline soils are unsuitable, as castorbeans are ranked at the bottom of the group of plants considered to have medium salt tolerance, below field corn and considerably below cotton (Richards, 1954). Wadleigh *et al.* (unpublished data, 1947) tested the CONNOR and WIEMAN castorbean varieties under three levels of NaCl: none, 0.1, and 0.2 per cent, based on the dry weight of soil. Dry weight of plants grown at the 0.1 and 0.2 per cent levels was only 60 and 23 per cent, respectively, of the dry weight of the controls. Both varieties responded similarly. It is concluded that this species does not show significant salt tolerance.

Castors, having little soil-binding ability, are not recommended on soils subject to erosion. Castors are not a crop for poor land, responding poorly on soils of low fertility. Extremely fertile soils, however, produce a rank vegetative growth.

5. *Temperature*

Van Horn (1952) reported that castors tend to do best where temperatures during the entire growing season remain fairly high, but not too high, as they suffer from extremely high temperatures. He noted a blasting of flowers and a failure to set seed when the temperature exceeded 105°, especially if the available soil moisture was low. Failure to set seed because of high temperature injury may result under dry-land or irrigated conditions, whenever moderate or severe wilting of the leaves occurs during the morning hours.

6. *Insects*

The castorbean plant is not toxic to insects. Cutworms and wireworms can reduce stands. The corn borer has been reported to invade the stems. Occasional damage has been caused by green stink bugs and the false chinch bug. The striped-yellow army worm feeds on the foliage, as do webworms, caterpillars, grasshoppers, and leafhoppers. Thrips, spider-mites, and leaf miners also damage the leaves. It has recently been reported that lygus bugs in Arizona, especially the nymphs, damage the racemes by injuring the pedicels. To date insects have not been a serious problem. However, if production expands over a period of years, insect populations predatory to castors may build up, making control measures necessary. For example, leaf miners have been observed in increasing numbers in some of the castor breeding nurseries.

D. Varieties

There is a large number of castorbean varieties. Many varieties developed for mechanized production have been grown since 1947. This is to be expected, for the breeder had considerable variation from which to select. Consequently, in a relatively short time a number of indehiscent varieties had been developed, most of them an improvement over their predecessors in yield or suitability for mechanical harvesting. Many varieties have been evaluated. Figure 4 shows varieties now being grown commercially.

(1) CIMARRON is an inbred or open-pollinated variety grown under nonirrigated conditions in Oklahoma, Tennessee, Arkansas, and Mississippi. This variety carries resistance to bacterial and Alternaria leaf spot. In any one year it may not be the highest yielding variety in the above mentioned states, but over a number of years, it has yielded better than the average of other varieties tested. CIMARRON is also used as a male parent in an F_1 hybrid; however, because of its tendency to produce low-growing branches (not desired in mechanical harvest), this hybrid has been replaced by hybrids that do not have this characteristic.

(2) Nebraska-145-4 is used as the female parent in producing commercial F_1 hybrids. No other available female line with a sex mechanism suitable for producing commercial F_1 hybrid seed also has the desired agronomic characters. N-145-4 is susceptible to bacterial leaf spot. At Davis, California, its yield is among the highest of the inbred lines. But this is not so in Arizona, and another female parent is desired for this area.

(3) PACIFIC HYBRID 6 is a pistillate F_1 hybrid. It is grown under irrigation in Arizona and California. It has replaced CIMARRON HYBRID and PACIFIC HYBRID 4 because of its higher yield and its better characters: few

branches and long racemes. Under average field conditions, PACIFIC HYBRID 6 is capable of producing 2,500 lb. of seed per acre, and yields as high as 3,500 lb. have been obtained. Under test plot conditions, yields of 4,000 lb. per acre are not uncommon, and more than 5,000 lb. have been obtained. Oil content has ranged between 50 and 55 per cent, depending upon environment.

FIG. 4. Current commercial [illegible] normal-internode, pistillate F_1 hybrid and dwarf-internode, monoecious inbred, 1957.

(4) 415 HYBRID is a pistillate F_1 hybrid quite similar to PACIFIC HYBRID 6 in plant conformation except that it flowers one or two nodes higher. It is currently being grown in Arizona and California. It appears to have a yield ability similar to that of PACIFIC HYBRID 6.

It should be pointed out that the above pistillate F_1 hybrids are pollinated by the monoecious segregates of the female parent. Some sibbing results in the female parent of the crossing block because of failure to rogue all the monoecious plants (see Section III, D).

(5) Dwarf-internode varieties were grown semi-commercially for the first time in 1956 on the Texas High Plains. The shortness of these varieties gives them much more tolerance to strong winds than normal-internode varieties. The reduced seed loss is an important character in the windy High Plains area. Because the available dwarf-internode varieties yield less than hybrids, they are not grown in Arizona and California, where wind tolerance is not a decisive factor. The dwarf-internode varieties DAWN and BAKER 296 are currently grown under irrigation on about 3,000 acres in the High Plains. It is expected that these varieties will soon be replaced by other dwarf-internode varieties now coming into greater use. Breeding programs under way are introducing the sex characteristics necessary for the production of hybrid dwarfs.

E. Culture

Castorbeans in the United States are grown in relatively close-spaced rows, 38 to 40 inches apart, to facilitate mechanized row-crop culture and harvest. In other countries, where production is not mechanized, castors are generally grown in widely spaced rows, sometimes interplanted with other crops. Since culture of castorbeans in close-spaced rows is a relatively recent development, available experimental information is small compared with that for established row crops. The varietal picture has changed rapidly. Cultural experiments conducted as recently as five years ago may not be applicable to the varieties currently being grown. Thus, much of the information presented here is based on grower experience.

1. Seedbed

Seedbed preparation is important. Tillage implements that help to break up hardpan are recommended. The seed bed may be prepared for flat planting or on beds. A practice popular in cotton seed bed preparation is recommended for castorbeans. Irrigation water is run in the furrowed-out land long enough to sub through the ridges or beds; using planters equipped with sweeps, enough dry soil is removed from the beds to permit planting the seed into 1½ to 3 inches of undisturbed moist soil. The advantage is that the seed is placed in soil of more uniform moisture than is the case when the seed bed is worked up prior to planting. Further, the racemes of castors grown on beds are higher above ground level, which facilitates mechanical harvesting.

2. Planting

To ensure prompt germination, castors should be planted as soon as possible after the soil warms. This is not always easy to arrange. Clendenin (1951) points out that, in a germinator, (1) temperatures below 63° F.

cause intermittent germination; (2) at least 63° F. is necessary for uniform germination; and (3) germination is not materially improved by temperatures above 63° F., although seedling development is accelerated. Van Horn (unpublished work, 1957) points out that some varieties need fluctuating temperatures for initiation of germination. The time of planting corn or early cotton coincides with castorbean planting time.

Because the seed is easily broken, special planter boxes are recommended, such as the inclined-plate type, designed to agitate the seed as little as possible (Schoenleber and Van Horn, 1953).

Castor seed requires moist soil for germination over a longer period than does corn or cotton seed. Therefore the seed should be planted well into moisture, the depth varying from 1½ inches to 3 inches, depending on how fast the soil might be expected to dry down to the seed. With early planting, a 1½ inch planting depth, well firmed with an open press wheel, is normally sufficient. But if strong, drying winds are imminent, it is well to pack the planted rows after the surface soil has dried to a depth of about ½ inch. Emergence of the castorbean may take 10 days to as many as 21 days. If necessary, a light harrow or rotary hoe may be used to break crusts and control weeds before emergence. When the curved hypocotyl, or crook, is near the soil surface, care must be taken not to break off the seedling.

A desired stand is about 12,000 plants per acre. Stands of 75 to 100 seedlings per 100 foot of row are satisfactory. Spacing trials have generally shown no significant difference in yield among stands within a spacing range of 6 to 36 inches within 38-inch rows. However, spacings closer than 12 inches within the row are not recommended, for the plants will be spindly. This is undesirable if strong winds are possible during the harvesting season.

3. *Weed Control*

Castors are not strong competitors against weeds. The only effective control thus far is cultivation, but only to a shallow depth, for castors have their main lateral roots near the soil surface. As mentioned above, pre-emergence weed control can be effected with a light harrow or rotary hoe. Proper timing of this operation can sometimes save the cost of hand hoeing.

4. *Irrigation*

As mentioned previously, about 2½ to 3½ acre-feet of water is required during the growing season if irrigation is the only source of soil moisture. Frequency of irrigation is very important. Too much water, especially before and during the early stages of first raceme development,

can result in a wilting of the leaves, just as occurs with too little water. Irrigation between the rows will reduce the chances of overwatering. The first irrigation is generally applied at the six- to eight-leaf stage or at the time the first raceme starts to develop. It is well to avoid overwatering at this time, by irrigating every other row. Subsequent irrigations will depend on temperature, soil, moisture-holding capacity, and depth of root penetration. Irrigations may be spaced by as little as 7 days to as much as 21 days. When irrigation is applied at 7-day intervals, the plants should be inspected for possible development of capsule molds (see Section IV, C, 1). The best indicator of irrigation need is the plant. The leaves should never be allowed to wilt during the morning hours. Castors in such state of stress can be expected to produce blasted or poorly filled seed and to lose some of their leaves resulting in stimulation of weed growth because of inadequate shading. If irrigation water is limited, each furrow is irrigated every other time throughout the season.

Castors are well adapted to subirrigation, developing a deep root system in soils where subirrigation is possible. This permits complete drying of the surface soil, reducing weed problems. As with surface irrigation, overwatering is possible. Therefore the water level must be controlled.

5. *Fertilization*

Fertilizer requirements of castors may vary considerably with location. Because of the relative smallness and newness of the crop in the United States, little information is available on fertilizer requirements under generalized sets of conditions. Deficiency symptoms for nitrogen, phosphorus, potassium, iron, calcium, and magnesium have been demonstrated under controlled conditions (Tucker, 1953). However, except for nitrogen, the relationships of deficiencies to symptoms under controlled and field conditions have not yet been established.

Castors generally should receive 40 to 100 lb. of nitrogen per acre. Applications at the latter rate may well be split during the growing season. It is possible to overfertilize with nitrogen, producing rank vegetative growth. Where cereals respond to phosphate, field observations indicate that castors will also benefit from an application of 40 to 50 lb. of superphosphate at planting time.

F. Harvesting

As already mentioned, commercial production of castorbeans in the United States depends on mechanical harvesting. Harvesters currently in use remove the capsules from the standing plants and hull, or shell, the seed (Schoenleber *et al.*, 1957; Coppock and Schoenleber, 1957). The cap-

sules are shaken from the plant by a low-frequency vibration induced in the branches by knockers that hit the plant near the base, about 8 to 10 inches above the ground. The hulls are removed from the castor seed in a huller-cleaner mounted on the harvester, and clean seed is elevated to a storage bin also mounted on the harvester. At the edge of the field the seed is dumped from the bin into a truck and hauled to the crushing plant or receiving point.

Because the castor plant produces racemes sequentially, the capsules are in all stages of development at harvest time: mature capsules, green capsules containing filled seed, and green capsules containing unfilled seed. Therefore the green capsules must be dried and the leaves removed before mechanical harvesting. This may be accomplished by frost or by chemical defoliants. A temperature of 28° F. for about 4 hours is required. Defoliants are applied from an airplane. Two applications are sometimes necessary if the plants are in an active stage of growth. Harvesting is usually possible 10 to 15 days after defoliation. As previously mentioned, the relative humidity must be 45 per cent or less for the harvester to operate efficiently.

G. Cropping Sequence

Some precautions must be taken with crops that follow castorbeans. Present mechanical harvesters leave 3–10 per cent of the crop in the field, the loss increasing with plant height, which may range from 3 to 12 feet or more. The unharvested seed may present a volunteer problem in the following crop. To reduce this problem, the castor seed should be covered shallowly soon after harvest to permit germination. Irrigation will help bring up the volunteer crop. Castor seeds turned a foot under have been observed to emerge late in the following summer.

The poisonous seed must be kept out of crops grown for animal feed. Taken in sufficient quantity the young plants are also poisonous. Livestock will rarely eat the castor plant except when forced to by lack of food or the mixing of castor plants with their feed so they have no choice. Despite the castorbean's unpalatability, it would be unwise to follow castors with a pasture crop. However, castor plants are easily destroyed. Once the plant is cut off below the first node (usually two or more inches above ground level) it will not make regrowth.

Volunteer castorbeans offer very little competition in cereal grains, which are planted during the cool part of the growing season and already shade the ground before the castors emerge. Those that emerge in open areas of a cereal field can be controlled with 2,4-D.

Numerous farmer reports have indicated that castors benefit the soil,

as measured by the performance of subsequent crops. It is believed that this results from some change in the physical structure of the soil, for tillage implements are reported to require less power than normal.

H. Marketing

Currently, oil mills that crush castorbean seed are located on the east and west coasts of the United States. They also crush imported castor seed. Because the seed is poisonous, mills that handle edible oils do not generally crush castorbeans.

The price of castor seed is determined by the price of the oil and pomace. Castor pomace is used only as a fertilizer because of its toxic constituents (see Section IV, A). It contains about 5.5 per cent nitrogen, 1.0–1.5 per cent P_2O_5, and 1.0–1.5 per cent K_2O. Its allergenic constituents, which are separate from the toxic constituents, present problems in marketing. Pomace could enter the channels of trade more easily if the allergens could be rendered impotent.

According to Woodward (unpublished, 1949), the Germans developed detoxification methods and, during World War II, used castor pomace in a variety of foods and feeds, including soy sauce, bouillon cubes, and soup stock. Woodward says this use was verified at the close of the war by a committee of the Joint Chiefs of Staff. Young (1951) has reviewed the contradictory results of detoxifying castor pomace and using it in feeding trials. Some workers reported that detoxified pomace in the ration was beneficial; others reported reduced growth or the loss of experimental animals. Needless to say, if an economical method could be developed to use the pomace as an animal feed, the value of this component would be increased and the price of the oil could be reduced, thus opening up additional markets.

V. The Future for Castorbeans

Mechanized castorbean production is in its infancy. Hybrid castorbeans suited to mechanical harvesting have been developed for only 8 years, and available commercially for but 4 years. A dwarf character is available that may find its counterpart in castors as it has in grain sorghums. Mechanical harvesters are new and few in number. A total of only 27 machines was available in 1957. Agronomic work on castors is relatively new, having been initiated 16 years ago. Breeding programs engaging the full time of plant breeders have been under way for but 10 years. Engineering research on field harvesting has been under way for a similar period. The achievement of mechanized production has not been easy. Varieties successful in the test plot often failed in the field; mechanical

principles successfully tested in the laboratory proved unsuited to field conditions. However, such failures stimulated new ideas and an exchange of information between workers in private industry and in public research agencies. An industry with such a background would seem to have the attributes necessary to an expanding future.

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SAFFLOWER

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I. Introduction

Though safflower (*Carthamus tinctorius* L.) is usually termed a new crop in the United States, it ranks in antiquity with most of the cultivated crops. For centuries, it was grown for its flower which provided a dye for clothing and food of Asian and European peoples. Only within the last century has it achieved the status of an oil crop, and only within the last twenty years has it come to the United States to stay.

A recent review by the writer (Knowles, 1955) discussed safflower from the aspects of production, adaptation, processing, and utilization. Although it was well established at that time as a commercial oil crop in California, it was evident that there was little stability about its production in other areas of the United States. With the exception of India, where safflower is grown on a large acreage, other countries were attempting their first commercial production of safflower as an oil crop, with varying success. One objective of this report will be a re-examination of the production pattern in the United States and other countries to learn to what extent it has changed. Perhaps new uses are in prospect. Have improvements been made in safflower, or are they in sight?

No attempt will be made to review the cultural practices for safflower, though there is considerable information available (Claassen and Hoffman, 1950; Klages, 1954; Knowles, 1955; Morrison, 1954; Pittman and Draper, 1955; Riedl, 1955; Waring, 1957). There will be little said about either the processing of seed for oil, or research on the oil itself.

II. Distribution

Safflower has been grown for centuries in greater or less amounts over a vast area extending from central India westward to, and around, the

Mediterranean Sea. Its ancient northern limit would be southern Siberia and southern Russia. The countries of the Nile Valley have grown it also.

A. India

The acreage of safflower in India is many times that of all the rest of the world combined. In Bombay State alone there was 429,000 acres in 1953–1954 (Argikar *et al.*, 1957), little different from the 500,000 acres in 1900. Hyderabad State grows about 600,000 acres and Madhya Pradesh about 7,000 acres. Other areas grow insignificant amounts. It is often grown in association with other crops, either in alternating rows, or as a border about the field.

B. Other Countries of Asia and Europe

In Pakistan, Afghanistan, Iran, and most countries of the Near East the acreage has been small, most of it devoted to types grown for the color obtained from the flowers. Turkey had an average of 3,100 acres in the years 1950–1953 (Knowles, 1955), and the area is reported to have increased since then because the oil is needed in the manufacture of margarine (Ilisulu, personal communication).

The area in Israel has increased from 1,044 acres in 1949 to 6,960 acres in 1956 (Kostrinsky, personal communication). It is a dryland crop with an average yield in 1956 of 460 lb. per acre. The oil is used mainly for margarine.

The U.S.S.R. is reported to have had 121,000 acres in 1932 (Scheibe, 1938), but no data on recent production are available. Production in France (Knowles, 1955) decreased from 7,400 acres in 1949 to none in 1953, this a consequence of the depredations of the larvae of the safflower fly.

Safflower is under test in Greece (Panos, 1956). It was thought that safflower would be a desirable replacement for flax in dry areas.

C. Africa

In countries of North Africa safflower has been grown primarily as a garden crop for its flowers, with never more than a 1,000 acres for oil. The same is true of Egypt, though the area did reach 2,500 acres before World War II. Some 3,000 acres were grown in the Sudan in 1957 (Zain, personal communication).

D. Australia

In Australia safflower is grown in the wheat areas of the northwest part of New South Wales and southern and central Queensland (Kleinig, personal communciation). Yields there have ranged from 750 to 2,000 lb. per

acre. In 1956 an area of about 4,000 acres was sown to safflower, all of it dryland. It is estimated that 35,000 acres will be necessary to supply the need for alkyd resins.

E. Canada

Safflower was first established on a sizable commercial scale in Canada in 1957 (Hay, personal communication). Some 15,000 acres were grown in southern Alberta, all of it dryland as a replacement for wheat. The best fields were estimated to yield 1,000 to 1,200 lb. per acre. Apparently all of the seed was exported.

F. United States

Most of the safflower in the United States continues to be located in California (Table I). Since its introduction to the state on a commercial

TABLE I

Safflower Acreage and Production in California (1950 to 1956)

Year	Area: Sacramento Valley	Area: San Joaquin Valley	Area: Other areas	Total
1950 (acres)		18,244	1,632	23,000
1951 (acres)	9,220	5,108	2,672	17,000
1952 (acres)	34,179	4,131	3,350	42,000
1953 (acres)	44,375	728	1,897	47,000
1954 (acres)	25,646	400	1,914	28,000
1955 (acres)	53,927	880	2,162	57,000
1956 (acres)	83,983	845	2,172	87,000
1956 (production in cwt.)	1,398,480	11,815	36,055	1,444,200
1956 (yield, cwt. per acre)	16.6	14.0	16.6	16.6

scale in 1950, it has been grown in many areas, but there has been a shift of production to the Sacramento Valley. The shift has been encouraged by the poor performance of safflower under irrigation in southern areas of the state. In the Sacramento Valley it is grown dryland, but in many instances after an irrigated crop. It has often been placed in the rotation after rice.

Acreage in the western part of the northern Great Plains, principally in western Nebraska, eastern Colorado, eastern Wyoming, and eastern Montana, has fluctuated strongly, even though the first commercial acreage was established in 1946. A processing plant established at Longmont, Colorado, in 1949 has been dismantled recently. Another plant in operation at

Sidney, Nebraska, for some three years has used seed from 15,000 acres in that area in 1957, all of it dryland. Yields ranged from 300 to 2,000 lb. per acre.

Safflower was introduced on a commercial scale to eastern Washington in 1955, when about 7,500 acres were grown (Morrison, personal communication). Although planted in the spring as a dryland crop, it has been a replacement for fall sown wheat. Acreage has decreased since then because yields have been low compared to cereal crops, and not above 1,200 lb. per acre. Weeds have been difficult to control in safflower, and there has been some rain damage in the fall because of its late maturity.

In 1957 an estimated 15,000 acres were grown dryland in northern Utah and southern Idaho (Parkey, personal communication). The yield was estimated to range from 300 to 1,500 lb. per acre.

III. Adaptation

The adaptation of safflower and the characteristics of the plant affecting its success have been reviewed in detail (Knowles, 1955). Only a summary will be given here.

A. Water Relations

All parts of the plant seem to be very sensitive to moisture. Surface irrigation has led to a high incidence of root rot caused by *Phytophthora drechsleri* Tuck. (Thomas, 1951) or a species of Pythium (Cormack and Harper, 1952). Even varieties resistant to Phytophthora root rot have been difficult to irrigate in California. During the winter in California it has been killed rather readily by standing water. In spite of this, safflower has required a soil well supplied with moisture. Highest yields have always been obtained where subirrigation was practiced or surface irrigation was carefully controlled. In 1957 the low yields of many fields in California appeared to be associated with the presence of dry soil beyond a depth of about 4 feet. Shallow hill soils have not given high yields, and the reason may be that there is not a sufficient reserve of moisture. Under dry-land conditions yields have been much better on summerfallow than after a crop such as barley. Experience in Nebraska is the same (Claassen and Hoffman, 1950); moist soil to a depth of 3 feet prior to planting in April was necessary for a satisfactory crop.

The total water requirement of safflower has not been accurately determined. Experience in California indicates that it needs some 16 inches of soil moisture for a satisfactory crop. This is approximately the total annual precipitation where safflower is grown commercially in the United States (Table II). In California most of this moisture must be stored in

TABLE II

Long Term Average Temperatures and Precipitation in Areas of the United States Growing Safflower[a]

Month	Temperature °F for: Davis, Calif.	Walla Walla, Wash.	Pocatello, Idaho	Sidney, Nebr.	Precipitation (inches) for: Davis, Calif.	Walla Walla, Wash.	Pocatello, Idaho	Sidney, Nebr.
January	46.3	32.0	22.1	26.0	3.52	1.68	1.21	0.32
February	50.6	38.3	28.5	29.8	2.98	1.58	0.96	0.39
March	54.7	46.8	36.6	36.8	2.36	1.52	1.13	0.84
April	59.1	53.9	46.3	46.9	1.20	1.24	1.32	2.23
May	65.7	61.2	55.3	57.3	0.60	1.26	1.21	2.75
June	72.4	67.9	63.0	66.1	0.15	1.21	1.02	2.82
July	76.1	76.2	72.7	74.6	0.01	0.28	0.76	1.79
August	74.7	74.2	70.1	72.3	0.01	0.34	0.72	1.85
September	70.8	65.3	59.8	62.5	0.23	0.86	0.90	1.30
October	63.5	55.2	49.3	51.0	0.78	1.48	1.04	0.96
November	54.2	42.5	35.9	36.6	1.60	1.86	1.06	0.51
December	47.2	36.3	26.8	28.8	3.28	1.81	1.14	0.45
Year	61.2	54.2	47.2	49.1	16.72	15.12	12.47	16.21

[a] From United States Weather Bureau records

the soil, since safflower develops most of its growth after the spring rains stop. For maximum yields a total of about 25 inches of soil moisture will be required.

Above-ground portions of the plant are sensitive to moisture, at least in terms of susceptibility to attacks of pathogens. In early stages safflower appears to be quite tolerant of high atmospheric humidities. After the bud stage Botrytis blight will usually appear on the buds or flower if prolonged rains occur or fogs prevail. This disease has prohibited the production of commercial varieties in coastal areas of California. Coastal areas were not considered suitable for safflower in Australia (Anonymous, 1955a) though the reason was not given. High relative humidities in the early spring encourage the rapid increase of rust. Cercospora leaf spot has been more serious in the western part of the northern Great Plains when heavy rains occur (Claassen, 1949). In the areas of the United States where safflower is grown, the rainfall during the summer and early fall has been low (Table II).

Safflower is reputed to be a drought resistant crop. Actually this would appear to be true so long as there is a reserve of moisture in the soil. Its strong tap root will forage deeply for moisture, more deeply than the roots of cereal crops.

Hail storms, with stones up to 1 inch in diameter, have not caused serious damage to safflower in early stages of its development (Pittman

and Draper, 1955). After reaching a height of 6 inches it is as susceptible as other crops (Claassen and Hoffman, 1950).

B. Temperature

The minimum temperature tolerance of safflower depends upon the variety and stage of development. The variety WO-14 was undamaged by temperatures down to 9° F. at Camp Verde in Arizona, whereas temperatures down to 13° F. killed N-6 and N-10 (U.S. Dept. Agr., unpublished data). Once out of the rosette stage it is more sensitive to frost. When N-852 was growing rapidly in the Imperial Valley, temperatures of 24° F. almost completely killed it, whereas N-8 was damaged very little (Knowles, 1955). In Idaho spring temperatures of 28° F. damaged varieties to different degrees when they were about four inches high (Klages, 1954). A few degrees of frost will damage all varieties after flowering commences. Safflower appears to be tolerant of high summer temperatures if the roots have adequate moisture.

C. Growing Season

Where safflower is a spring sown crop the growing season should provide at least 120 days, if high temperatures prevail during the summer. In northern Idaho, where summer temperatures are low, it requires 145 days to mature (Klages, 1954). Varieties differ considerably in their rate of development (Table IX). At Davis the same variety planted at several dates from November to March will mature over a period of 10 days in early August.

When fall plantings are made in the Sacramento Valley, barley has usually been more successful than safflower. As plantings are delayed after January 15, safflower improves in its competitive position.

D. Soil

Safflower appears to be rather sensitive to the soil environment, quite apart from the moisture it may contain. Wherever safflower is particularly successful it has been on deep, fertile, and well-drained soils that are neutral in reaction. On such soils in California it has been strongly competitive with barley, whereas on shallow soils barley has been more productive.

Safflower is similar to barley in its tolerance of alkali under dryland conditions, but more sensitive than barley when irrigated. Boron injury has been found on the variety N-6 (Knowles, 1955).

In very heavy soils in California, it has sometimes been difficult to obtain stands. After the winter rains it may not be possible to work such soils until the late spring, when cultivation may dry out the seed bed to the depth of tillage. With no additional rain, it may be necessary to use special

seeding equipment to crowd away the dry soil and plant the seed down into moisture. With plantings made during the winter, heavy rains followed by dry winds have occasionally crusted the soil and reduced emergence.

IV. Botany and Inheritance

Safflower belongs to the tribe Cynareae of the Compositae. In this tribe are such genera as Cynara (artichoke), Cirsium (thistle), and Centaurea (star thistle). Cultivated safflower is an annual, but there are perennial species in the genus.

A. Roots

Safflower has a deeply penetrating tap root. Pugsley and Winter (1947) found roots to a depth of 7 feet with roots of wheat in adjacent plots going only to a depth of 4 1/2 feet. A single tap root was usually present, but sometimes strong branches extended out 2 to 3 feet. At Davis, Doneen (unpublished data) has found safflower taking moisture from the soil to a depth of 8 feet.

B. Stems and Branches

Safflower has a strong central stem terminating in a head, this being the first one to flower on the plant. Kupsow (1932) found that height varied greatly with the country of origin, and the same has been true at Davis (Table III and Fig. 1). Tallest types have come from the area ex-

TABLE III

Safflower Introductions Classified for Height at Davis, California, 1957

Countries of origin	Height in centimeters[a]							
	51–65	66–80	81–95	96–110	111–125	126–140	141–155	156–170
India, Pakistan	10	111	109	22	8	2	—	—
Iran, Afghanistan	—	—	—	—	6	1	1	—
Turkey, Syria, Israel	—	—	2	3	5	6	1	2
Russia, Rumania	—	1	1	—	3	—	—	1
France, Spain, Portugal	—	—	—	4	3	—	—	—
Morocco, Algeria	—	1	1	4	—	—	—	—
Egypt, Sudan, Kenya, Ethiopia	—	—	7	13	6	1	—	—

[a] For planting made Feb. 16; corresponding classes for safflower sown March 23 were 10 cm. shorter.

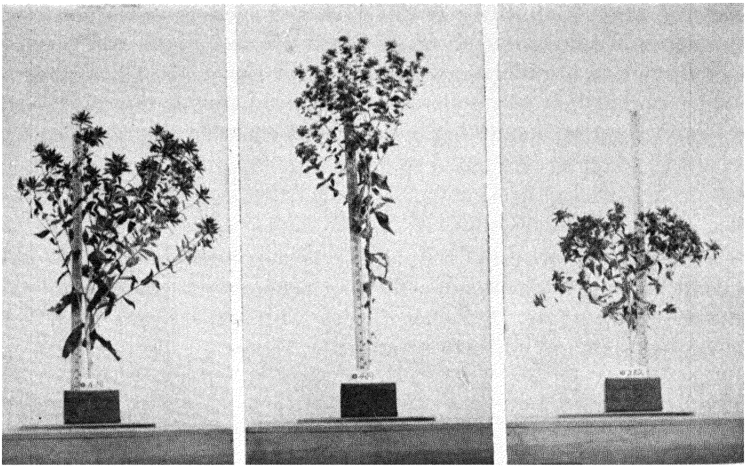

FIG. 1. Safflower plant types; left to right, N-10, P.I. 220,647 from Afghanistan, and 57–24 from India.

tending from Turkey to Afghanistan, and the shortest from India. Under California conditions, height is strongly influenced by date of seeding (Knowles, 1955). Plantings of the variety N-852 made in November, December, February, and March grew to 59, 55, 50, and 41 inches high, respectively.

Branches may be spreading or somewhat appressed to the stem. The number and location of the branches will vary greatly with the environment and the variety, and their development will govern the appearance of the plant.

Safflower produces a rosette of leaves prior to the development of the stem. The duration of the rosette stage is determined largely by temperature. If planted in the fall, stems will not develop until the following spring, but if sown in the spring the rosette stage will last only a few weeks. In this stage the crop is very susceptible to being overcome by weeds. Once the stems appear a good stand of safflower has considerable competitive ability.

C. Leaves and Spines

Lower leaves are entire in most varieties, and free of spines. Depending on the variety the upper leaves may vary from those completely without spines to those that are strongly spined. Claassen has established a spine index which is calculated by multiplying the number of spines on an outer involucral bract by the length in millimeters of either the longer

spines (Claassen *et al.*, 1950) or the estimated average (Claassen, 1952). The number of spines was observed to vary from 0 to 24, and the spine length from 1 to 6 millimeters. Though both Roa (1943) and Claassen (1952) reported that one major gene produced spines, the latter found that in some crosses modifying and perhaps complementary genes were involved.

D. Heads

Heads (Fig. 2) consist of tubular florets, surrounded by several series of involucral bracts. The heads will vary in number from 15 to 150, and in diameter from ½ to 1½ inches. Types with large heads have come from Afghanistan and adjacent countries or Egypt.

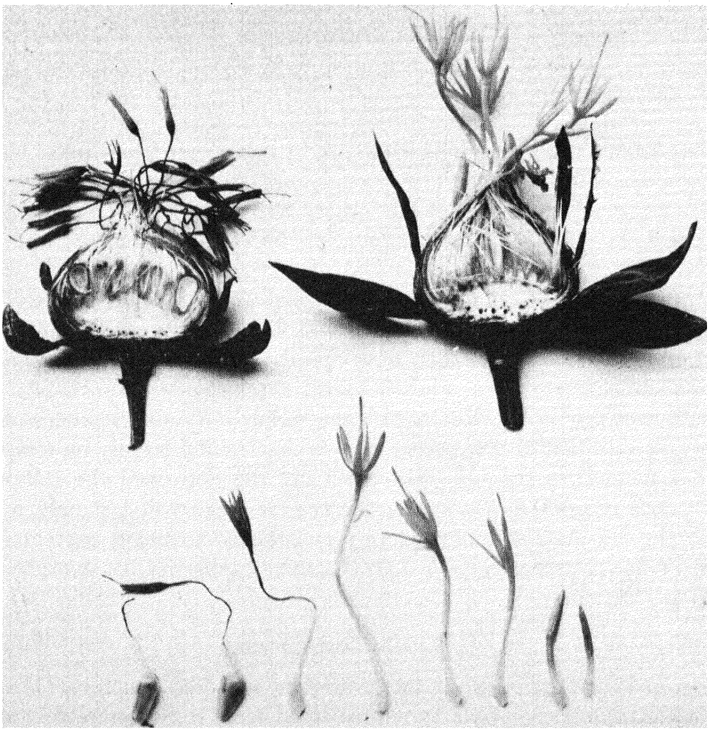

Fig. 2. Heads and flowers of safflower: upper left, the head after the flowers have withered and the seeds are well developed; upper right, when the first flowers appear above the bracts; lower, flowers at different stages of development.

The lower bracts of the involucre reflect the characteristics of the upper leaves. They vary in number and in shape from orbiculate and elliptical to lanceolate. The inner bracts are elongate, imbricated, and usually have a spinescent tip. White hairs may be present on the outer side of the inner bracts. Sabnis and Phatak (1935) classified their varieties as having the inner bracts either smooth and green or felted and white.

The number of florets will vary from 20 to 100 depending on the variety and environment. Receptacles are flat or slightly curved, and are covered with abundant bristles. These bristles may become a problem at harvest time, when they collect in the radiators of combine engines causing them to heat.

E. Flowers

Flowers are tubelike (Fig. 2) with a five-pointed tip. Anthers are united into a tube, with their filaments free and attached to the corolla. The style is completely surrounded by the anther tube.

Flowering starts at the margin of the head, and proceeds centripetally, 3 to 5 days being required for its completion. Considering all the heads of the plant, flowering may extend over a period of 10 to 40 days. Flowering occurs in the early morning. This is accompanied by elongation of the florets, with the projection of the style beyond the anther tube. The brush-like stigma picks up pollen in the process, since anther dehiscence occurs prior to this elongation.

Table IV shows flower color types recognized in classifying introductions grown at Davis in 1957.

TABLE IV

Flower Color Types Recognized in Classifying Introductions Grown at Davis in 1957

Type	Bud stage	In bloom	Wilted
1	White	White	Grayish white
2	Light yellow	Light yellow	Grayish white
3	Light yellow	Light orange base	Orange base
4	Yellow	Yellow	Yellow
5	Yellow	Yellow	Light orange base
6	Yellow	Yellow	Orange
7	Deep red	Reddish orange	Deep red
8	Yellow, base and tips of lobes orange	Like the bud	Orange

Kupsow (1932) recognized types 1, 4, 6, and 7, and Claassen (1952) recognized all of them but Type 5. Howard *et al.* (1915) and Khan (1929) did not list Type 5 or 8, but found the following variations of Type 6:

flower buds yellow with a red dot at the apex; flower buds yellow with a trace of red near the apex; flower buds yellow but reddish near the base; flower buds deep red with a yellow apical point. Sabnis and Phatak (1935) felt that some of these red coloration variations of Type 6 were due to aphis attack, and used only Types 1, 4, 6, and 7 or slight variations thereof in classifying Indian types. Variations of yellow and orange would appear to be the most common colors, with deep red being abundant in Afghanistan and adjacent countries (Kupsow, 1932).

Claassen (1952) has worked out the inheritance of flower color, and finds Types 1, 2, 4, 6, and 7 to be due to four independently inherited pairs of genes.

F. Natural Crossing

The most comprehensive study of natural crossing in safflower (Claassen, 1950) indicated that the amount is dependent upon variety and insect activity. White or red flowered plants, which were taken from varieties that were predominantly orange flowered, averaged 34.2 ± 5.8 per cent outcrossing, with the range from 8.3 to 100 per cent. F_2 plants with recessive flower colors had an average of 11.5 per cent outcrosses, with no account being taken of those effected by pollen carrying the recessive gene for flower color. Among 25 S_3 lines selected for high yield and high oil content there were 22 with an average of 12.5 per cent or less natural crossing, and 3 with 22.5 per cent or more. When five lines with a recessive flower color were sown between those with the dominant colors, there was an average of 18.6 per cent outcrossing (Table V), with no allowance for

TABLE V

Natural Crossing in Five Open Pollinated Safflower Lines Grown Between Rows of a Dominant Tester[a]

Line no.	No. of plants	Natural crossing per cent: Average	Range
33	9	13.3	9.8–19.4
34	55	19.8	4.9–83.0
48	20	28.8	9.0–93.6
49	19	15.1	6.8–54.5
50	19	17.1	0.0–59.6
Average	—	18.6	—

[a] After Claassen *et al.* (1950).

sibcrossing. Studies in India (Howard *et al.*, 1915; Kadam and Pantakar, 1942) gave similar results.

Claassen (1950) showed in addition that the same line might have plants with marked differences in degree of natural crossing (lines 34 and 48 in Table V). Where plants showed a high degree of natural crossing, their seed yields tended to be low, and their progenies showed marked hybrid vigor in the outcrosses. This prompted Claassen to suggest the use of such lines in the production of synthetic or hybrid varieties.

If the stigmas, stamens, and parts of the corolla tubes and styles were removed in the early morning, the percentage seed set was negatively correlated with the amount of natural crossing (Claassen, 1950). This suggested that plants with little natural crossing were fertilized early in the day, perhaps before insects became active.

Natural crossing appears to be caused by insects. Claassen (1950) in experiments with cages of wire screen or cheese cloth found that caged plants showed 0 to 3.2 per cent natural crossing, and uncaged plants 6.3 to 58.2 per cent. Under screened greenhouse conditions, when all insects were excluded, natural crossing was reduced to zero. Many insect species were found on safflower heads in western Nebraska, the most common being two species of bees, *Halictus pictus* Crawford and *Agapostemon radiatus* Say, and a beetle, *Chauliognathus basalis* Lec. Kadam and Pantakar (1942) considered honey bees (*Apis mellifera*) to be the main agent in cross pollination, and the same belief is held in California.

Wind does not seem to be an agent in cross pollination. Claassen (1950) found that slides with a thin film of vaseline on them did not collect safflower pollen when placed 30 to 48 inches above the ground in the safflower nursery. Scattered clumps of four or more pollen grains on slides 18 inches above the ground were considered to have originated from florets above the slides. Kadam and Pantakar (1942) reduced contamination of improved strains to negligible proportions by isolating them with a distance of 100 feet and placing some other crop such as wheat in the interval.

G. Artificial Crossing

Controlled crosses in safflower have been difficult, this being a consequence of the structure of the flower (Fig. 2) and the fact that it will yield only one seed. Claassen (1950) has described a satisfactory technique of emasculation. A bud is selected which will provide its first flowers on the following day. The tops of the bracts are cut away to reveal the entire anther column. Then all but the outer two rows of florets are removed with scissors. Sharp pointed tweezers are used to split the corollas and

anther tube and remove them. After all the florets of the head, usually 10 to 30, are emasculated, the head is soaked for 10 seconds in 57 per cent ethyl alcohol, and rinsed in water. The head is then bagged. Pollination the following morning is usually successful if the florets have elongated. The writer has used this technique of emasculation on species of Sections II and IV of the genus. For cultivated safflower, emasculation has been simplified by squeezing the floret with sharp tweezers just below the attachment of the anthers. If the corolla is gently bent, it will break at the point where it was squeezed, but the style will remain intact. Then the corolla and anther tube together can be gently and slowly slipped off the style. While a number of styles do break in this operation, it can be done quickly, and it does minimize the amount of escaped pollen.

H. Seed

The seeds, or more correctly, the achenes, of safflower are white or cream in color. Their composition (Claassen and Hoffman, 1950) is: oil, 26 to 37 per cent; protein, 12 to 22 per cent; moisture, 5 to 10 per cent; and hull, 35 to 52 per cent.

The high hull content has handicapped the crop commercially because it has reduced both the oil content and the protein content of the meal. It has varied with varieties from 38 to 62 per cent (Claassen *et al.*, 1950; Pugsley and Winter, 1947).

From crosses of cultivated safflower and the black seeded wild safflower of India (*C. oxyacantha*) it has been possible to obtain a range of seed color from black through various shades of brown and variable amounts of mottling to white. From the appearance of the F_2 plants it would seem that several genes are involved in hull color. The color of the kernel coat (seed coat proper) may vary from white, through yellow and light brown to dark brown (Von Kursell, 1939). It is not known to what extent seed and kernel colors may affect the color of the oil.

If pappus is present on some seeds, it is found on those in the center of the head. It may range from complete absence to presence on almost every seed. One major gene and some modifiers appear to determine the presence of pappus (Claassen, 1952).

Most safflower varieties have seed that is obpyramidal in shape with four pronounced ribs giving the seed a rhombic appearance in cross-section. Among 26 selections, Argikar *et al.* (1957) found that the weight of 100 seeds varied from 3.54 to 7.55 grams.

I. Sterility

One form of sterility was found by Claassen (1952) to be due to one recessive gene. The cytological basis of the sterility was not determined,

but the flowers appeared to be normal at flowering time. At maturity, however, they had few or no seeds, and seed set was not increased by artificial pollination. Deshpande (1940) and Claassen (1952) reported the occurrence of a sterile type with a single terminal head and no florets, this type being determined by a recessive gene.

V. Cyto-Taxonomy

A. Cultivated Safflower

Cultivated safflower has 12 pairs of chromosomes (Patel and Narayama, 1935; Richharia and Kotval, 1940). One report of 10 pairs (Gregory, 1935) appears to be the only exception.

Pollen mother cells of 24 introductions from different countries and 8 selections from the nursery at Davis were examined for their chromosome numbers, using standard cytological techniques (Table VI and Fig. 3). In

TABLE VI

Chromosome Number and Pairing Behavior at First Metaphase in Pollen Mother Cells of Introductions and Selections of Safflower

Origin or selection no. 1955	No. of intro-ductions	No. of plants	No. of PMC	Chromosome numbers					
				Closed II		Open II		I	III
				Av.	Range	Av.	Range	Av.	Av.
Israel	3	3	19	9.3	12-5	2.7	0-7	—	-
Sudan	9	9	176	8.5	12-5	3.5	0-7	--	--
Nebraska selections	5	6	83	9.0	12-4	3.0	0-8	—	-
Ethiopia	1	1	29	7.3	11-2	4.7	1-10	--	—
Iran	2	2	39	9.2	12-7	2.7	0-5	0.1	—
Morocco	1	1	101	7.4	12-3	4.6	0-9	—	--
Morocco	--	1	24	8.46	10-6	3.21	1-6	0.67	0.33
220, 224, fasciated	—	2	25	8.6	11-5	3.4	1-7	—	—
199, 456, partly sterile	-	2	46	8.0	11-5	4.0	1-7	--	—
32, 306 some heads aborted	—	3	95	8.7	12-4	3.3	0-8	--	—
27 open bud	—	1	52	8.2	12-4	3.8	0-8	0.02	--
412 cut leaf, large head	—	2	83	7.4	11-5	4.6	1-7	—	—

all but one plant there were 12 pairs of chromosomes. The one exception was a trisomic found in an introduction from Morocco. Two heads on the trisomic plant produced 47 aborted and one normal seed (2.2 per cent), whereas two heads on a normal plant of the same introduction produced 43 aborted and 13 normal seeds (30.2 per cent). Both plants were grown in a small pot in the greenhouse. All selections and introductions showed

more open bivalents at first metaphase than expected, although no definite reason can be advanced for this. The possibility of structural differences in paired chromosomes was ruled out because no multiple chromosome associations or anaphase bridges accompanied by fragments were found. The phenomenon may be a consequence of the failure of chiasmata formation in both arms of the paired chromosomes, although this could not be determined in diakinesis and diplotene because the chromosomes did not stain well in these stages. Chromosomes did not differ greatly in size and had median centromeres.

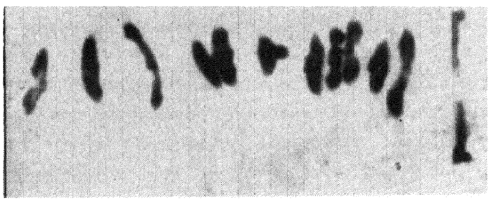

FIG. 3. Chromosomes of safflower (*C. tinctorius*) at first metaphase of microsporocytes ($\times$ 2025).

B. OTHER SPECIES

There would appear to be some 25 good species of wild safflower, all of them indigenous to the area about the Mediterranean Sea, with some extending through Asia to India and Afghanistan, and others going down the Nile Valley. They present a wide variety of types, from those that are similar to the cultivated species to those much different. Most are spiny, but at least one is spineless; a few are perennials; some have yellow flowers, and others blue.

Ashri (1957) and Ashri and Knowles (1957) found from studies of 11 species that there were four chromosome numbers ($2n = 20$, 24, 44, and 64). They were made the basis for four sections in the genus. The basic chromosome numbers were believed to be 10 and 12, not 8 and 12 as suggested by Darlington and Wylie (1956).

C. SECTION I ($2n = 24$)

Section I contains the annual species *C. tinctorius* L. (cultivated safflower), *C. palaestinus* Eig (wild safflower from the Negev Desert), and *C. oxyacantha* M.B. (the wild safflower of India). All three could be readily crossed, and yielded fertile F_1 and F_2 hybrids. Deshpande (1952) obtained similar results in crosses of cultivated safflower with *C. oxyacantha*. The latter species differs distinctly from cultivated safflower in having

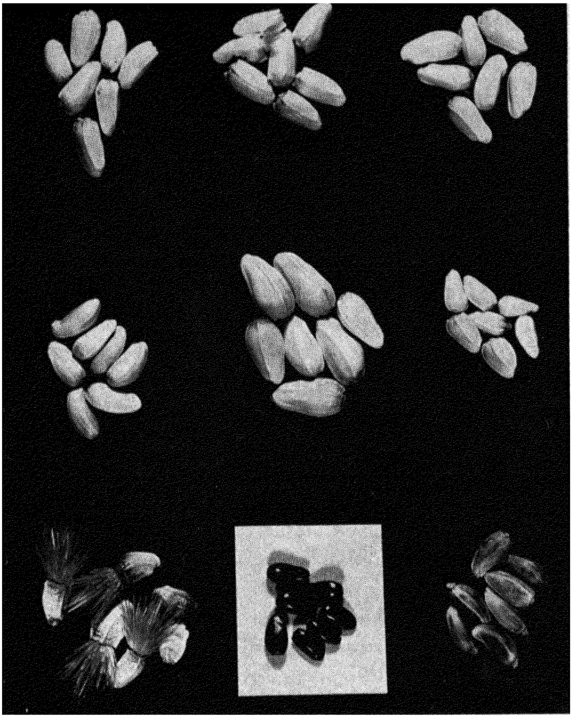

FIG. 4. Safflower seeds (actual size): top row, left to right, N-10, PACIFIC-1, and N-6; middle row, left to right, WO-14, large seeded introduction from India, and small seeded introduction from Afghanistan; bottom row, left to right, *C. palaestinus*, *C. oxyacantha*, and thin hulled mutant of Rubis.

seeds that are oval shaped in cross-section, free from pappus and usually colored (Fig. 4). The seeds of *C. oxyacantha* shatter readily at maturity, whereas cultivated safflower is resistant to shattering. *C. palaestinus* shatters its seeds also, but has seeds similar in shape to those of cultivated safflower (Fig. 3). The seed usually has a pappus, and just below the pappus it is brown in color. The flower color of both wild species is within the range of that of cultivated safflower.

Two perennial species with 12 pairs of chromosomes appear to belong to another group or groups. *C. arborescens* L. has yellow flowers, and is found in Spain and adjacent areas of North Africa. *C. caeruleus* L. has blue flowers, and ranges from France to Kashmir. Neither has been successfully crossed to other species with 12 pairs of chromosomes.

D. Section II ($2n = 20$)

Section II includes *C. alexandrinus* (Boiss.) Bornm., *C. tenuis* (Boiss.) Bornm., *C. syriacus* (Boiss.) Dinsm., and *C. glaucus* M.B., all found on the eastern side of the Mediterranean Sea. All have blue or pink flowers, and the first three are similar morphologically. *C. glaucus* differs from the others in having an open growth habit, larger heads, and ovate rather than linear involucral bracts. F_1 hybrids were obtained from crosses of cultivated safflower with *C. glaucus* and *C. tenuis*, from a cross between *C. palaestinus* and *C. tenuis*, and from a presumed natural cross between *C. oxyacantha* and *C. tenuis*. The F_1 hybrids showed very few bivalents at first metaphase in microsporocytes and were sterile.

E. Section III ($2n = 44$)

Section III has only one species, *C. lanatus* L., which is found over the entire range of the genus. The dense and long pubescence on the leaves and bracts of this species gives it a woolly appearance. Yellow is the most common flower color, but one collection from Spain has had some plants with white flowers. It is presumed to be an amphiploid of species of Sections I and II.

Crosses have been made with *C. tinctorius* and *C. oxyacantha* when they were used as the female parent. At meiosis of the hybrids there were from 1 to 7 bivalents, much less than the 12 expected if these species in Section I were involved in the production of *C. lanatus* through amphiploidy. When *C. lanatus* was crossed with species of Section II the microsporocytes of the hybrids had a mean of 5.03 to 8.13 bivalents at first metaphase, suggesting that some species in Section II did in fact contribute 10 pairs of chromosomes to *C. lanatus*. All hybrids were sterile.

F. Section IV ($2n = 64$)

Section IV includes only one species (*C. baeticus* (Boiss. and Reut.) Nym.), which is found in the Iberian Peninsula and adjacent areas of North Africa. This species has light yellow flowers. It is presumed to be an amphiploid of *C. lanatus* and some species in Section II. When *C. baeticus* and *C. lanatus* were crossed, the microsporocytes of the F_1 at first metaphase had 21.94 paired chromosomes, the number that would be expected if 22 of the chromosomes of *C. baeticus* came from *C. lanatus*. Crosses of *C. baeticus* with species of other sections were not successful.

G. Importance of the Weedy Species

Two of the weedy species are established in a limited way as weeds of roadsides and range areas in California (Howell, 1945; Ashri and Knowles,

1958). *C. lanatus* was found in areas adjacent to, or not far removed from, the Pacific Ocean, and *C. baeticus* in areas further inland.

The wild safflower of India (*C. oxyacantha*) is considered a useful plant for desert areas of India, though it is recognized as a serious weed of cultivated crops (Deshpande, 1952). Both this species and *C. palaestinus* may be sources of genes for resistance to disease, to insects and to drought. Some of the weedy species have shown immunity to rust and much more resistance to frost than cultivated safflower.

H. Evolution of Cultivated Safflower

Of the species that have been studied, *C. oxyacantha* and *C. palaestinus* would be the most likely ancestors of cultivated safflower. *C. oxyacantha*, however, is unique in the genus in having seeds that are oval shaped in cross-section and free, or almost always free, of pappus. If it is an ancestor of cultivated safflower, some other species must have contributed both the four-angled shape characteristic of cultivated safflower and the pappus. Kupsow (1932) believes that *C. lanatus* was the other species, and points out that cultivated safflower is best established in the area where *C. oxyacantha* and *C. lanatus* overlap. Ashri's studies (1957) would indicate that this is unlikely, since *C. lanatus* is an amphiploid and its crosses with *C. tinctorius* are sterile. There is a need for more information on the distribution and variability of wild species closely related to cultivated safflower before any firm conclusions can be made on the pattern of evolution. Kupsow believed there were two primary centers of maximum diversity in cultivated safflower. One was in mountainous Afghanistan and the other in mountainous Ethiopia.

VI. Utilization

For several hundred years safflower was grown primarily for its flowers, the red color being preferred. The dried flowers are still ground and used in a minor way as coloring in foods. Carthamin, a red dye which may be extracted from the flowers, was used extensively as late as a century ago to color cloth. It is still used for this purpose in parts of northern India and adjacent countries. It is rather remarkable that safflower has become adapted so quickly for other purposes. Except for recent developments, another review (Knowles, 1955) will give more details than are presented here.

A. Whole Seed

Recently there has been considerable interest in ground mixtures of safflower seed and barley as feed for dairy cattle (Pittman and Draper,

1955). The safflower seed, besides increasing the protein and fat content, reduces the dust in the hammerhill and gives a product that will hold together and be eaten up completely. Safflower is being incorporated into some patented pelleted products for the same reason. A sugar company is reported to be considering the use of crushed seed or meal in mixtures with beet pulp.

B. Oil

Until recently interest in, and research on, safflower oil in the United States was in relation to its value as a drying oil for paints, varnishes, and related products. The oil has been adaptable to the production of alkyd resins, which in turn are used in making enamels. Because the oil has no linolenic acid in its composition (Table VII) it has no after-yellowing

TABLE VII

Characteristics of Safflower, Linseed, and Soybean Oils[a]

Characteristic	Safflower	Linseed	Soybean
Iodine value (Wijs)	140-152	175-190	131-140
Color (Gardner)	6-10	8-11	8-11
Viscosity (G-H)	A–	A–	A–
Saponification no.	186-193	189-195	190-198
Acid value	0.3 to 3	0.7 to 4	0.8 to 3
Specific gravity 25°/25° C	0.922-0.927	0.930-0.934	0.924-0.930
% Unsaponifiable	0.3-1.0	1.0-1.5	1.0-1.5
% Saturated acids	6.6	9.6	13.2
% Oleic acid	16.4	20.1	30.2
% Linoleic acid	76.7	19.5	51.2
% Linolenic acid	0.3	50.8	5.4

[a] Cagan and Crowley (1952).

properties. The literature in this regard has already been reviewed (Knowles, 1955; Anonymous, 1955b).

Several countries have used safflower for edible purposes, India, Japan, France, Israel, and Turkey being among them. In the United States there has been some recent interest in the oil as a food, this interest stemming from reports that linoleic acid has some therapeutic value in preventing atherosclerosis. In a recent review Van Itallie (1957) states that studies have shown that vegetable fats, when substituted for animal fats in the diet, will reduce the cholesterol content of the serum, and that the factor in vegetable fats that correlated best with the reduction was the degree of unsaturation. He points out that this relationship is still inferential. He feels that, while certain vegetable oils effect a striking reduction in serum

cholesterol, there is room for a great deal of carefully controlled and prolonged experimentation to prove definitely that linoleic acid is the fatty acid mainly involved. Eagle and Robinson (1956) are even more sceptical; they feel that the literature on the relationship between diet and cholesterol content, and between cholesterol content and atherosclerosis is confusing and contradictory. If it is shown that linoleic acid will reduce the incidence of atherosclerosis, then safflower would appear to be the best natural source. At least two pharmaceutical companies now offer products containing safflower oil.

The Waring Blender technique for oil analyses, as described by Kennedy and Unrau (1949), has been used at Davis because it proved to be rapid and accurate. Johnson *et al.* (1956) found that a rapid dielectric method could be utilized. It was as simple, accurate, and practical for safflower as it was for soybeans and flax.

C. Meal

The high fiber content of safflower meal (Table VIII) has made it

TABLE VIII

Comparison of Safflower Hay and Seed Products with Other Feeds

	Safflower					
	Hay[a] (%)	Hulls[b] (%)	Undecorticated meal[b] (%)	Decorticated meal[b] (%)	Linseed meal[c] (%)	Alfalfa hay (good)[c] (%)
Moisture	9.0	8 7	8.0	8.0	8.7	9.6
Ether extract (oil)	2.2	4.7	6 0	7 6	6.4	1.8
Crude protein	11.2	3.8	19.0	36.0	35.3	14.3
Crude fiber	28.6	53.1	33.0	17.5	8.0	29.6
Ash	7.8	1.4	4.0	7.4	5.4	8.2
N-free extract	41.2	28.3	30.0	23.5	36.2	36.5
Total digestible protein	7.9	—	15.2	32.0	30.7	10.3
Total digestible nutrients	59.8	—	50.4	66.0	78.4	50.3

[a] Scharrer and Schreiber (1940): on the basis of 9.0% moisture.
[b] Goss and Otagaki (1954).
[c] Morrison (1947).

difficult to market in competition with other meals having more protein. As a livestock feed, however, it has been equal to other oilseed meals, if comparisons were made on the basis of equal amounts of protein (Baker *et al.*, 1951; Faulkner and Paules, 1952). As a poultry feed, the high hull

content has been undesirable. In the United States it has not been found practicable to remove the hulls in processing to permit the production of a decorticated meal. The decorticated meal has been satisfactory in rations for laying hens (Grau and Zweigert, 1953) but not for young chicks (Kratzer and Williams, 1951).

D. Miscellaneous

In California safflower stubble is used as pasture for sheep, but it should be cut short to permit the sheep to move through it easily. The hulls alone were not a satisfactory substitute for grain hay in a fattening ration for steers (Ramsaur, 1954).

VII. Improvement

As an oil crop safflower has given a good account of itself, when it is considered that for many centuries it was grown and utilized for its flowers. Until fifteen years ago no serious effort had been made in the United States towards making safflower a better crop.

A. Oil Content

The success or failure of safflower as a commercial crop in the United States has been determined by the oil content of the varieties grown. The efforts of Rabak (1935) and others twenty-five years ago to establish safflower failed because the varieties had less than 30 per cent oil. Although the present varieties with 34 to 36 per cent are satisfactory, safflower would compete even better with other oil crops if the oil content could be raised to 40 per cent.

Claassen *et al.* (1950) have studied in some detail the association between oil content and several morphological characters, their studies being based on measurements of F_2 plants from a cross of N-1 and N-8. As expected (Table IX) there was a high negative correlation ($r = -0.77$) between oil content and hull content. Nevertheless, the time involved in making hull measurements precluded their use in evaluating selections. As an alternative they suggest the use of an estimate of oil content based primarily on the number of seed with incomplete hulls and a "thumb nail" cutting test. It was difficult to cut seed with less than 26 to 30 per cent oil, and easy with 35 to 40 per cent. Their estimates and the actual values agreed very closely ($r = 0.93$). They warned, however, that accurate estimates could be achieved only with practice and familiarity with safflower seed, and that it could not be used where the range of differences was 2 to 3 per cent. The accuracy of estimates would be affected by the oil content of the kernel (or seed in the strict botanical

TABLE IX

Correlation Coefficients for the Interrelationships between Oil, Hull, Seed Size, and Degree of Spineness in 372 F_2 Safflower Plants of Cross No. 942[a]

	Hull	Seed size	Spineness
Oil	-0.77[b]	0.22[b]	0.20[b]
Hull	—	-0.02	-0.13[c]
Seed size	—	—	0.09

[a] From Claassen *et al.* (1950).
[b] Significant at the 1% level.
[c] Significant at the 5% level.

sense), which was found to vary over a range of 43.1 to 58.1 per cent in selected F_2 plants.

Although Claassen and his associates found significant correlations between oil content and other plant characters (Table IX), they were too small to be of much value in a breeding program. The positive correlation between spininess and oil content has been observed in many breeding programs, and no spineless varieties have been released with oil contents equal to the better spiny varieties.

Since there was no correlation between seed size and hull content, this would suggest that the positive correlation between seed size and oil content is influenced by the oil content of the kernel. It would seem that improvement of the oil content of safflower seed must keep in mind both hull content and oil content of the kernel.

The commercial varieties of the United States that have had the highest oil content stem back to introductions from Egypt. In Australia high oil content has been obtained in introductions from Egypt, the Sudan, Syria, and Israel (Anonymous, 1955a). While all of Kupsow's materials had less than 30 per cent oil, those with the greatest amount came from Afghanistan (Kupsow, 1932).

Claassen (personal communication) now has selections with an oil content of 40 per cent or better, and feels that multiple factors determine the inheritance of high oil content in his materials. Rubis (1957) has found a mutant with thin hulls, this character being due to a single recessive gene. The mutant type had very weak stems, and the weak stems appear to be linked in inheritance to the thin hulls.

Open-pollinated seed from two plants with thin hulls was supplied by Rubis and grown at Davis in 1957. From each of the two progenies only one plant was obtained with thin hulls, the balance, five in one case and

six in the other, having thicker hulls. This would support Rubis' belief that the selection with thin hulls is highly outcrossed. The oil content of the thin hulled plants with the corresponding average oil contents of four related outcrosses were respectively 41.3 and 32.4 per cent, and 43.4 and 35.7 per cent. The values for N-10 and PACIFIC-1 were 33.5 and 33.8 per cent respectively. This gene for thin hulls, if it can be separated from genes for some undesirable characters, should make safflower much more productive of oil.

B. Iodine Value

Many analyses of safflower varieties and single plant selections have been made at Davis, with no marked departures from a range of 138 to 145. It was surprising, therefore, to learn that a safflower type had been found by Horowitz and Winter (1957) with a very low iodine value. Two plants in an introduction from India gave iodine values of 105 and 100, when that of the bulk sample was 146. Progenies of the latter plant when inbred for two generations ranged from 88 to 97. The fatty acid compositions of the "normal" and "variant" were as tabulated.

	Normal	Variant
Iodine value	148	91-101
Saturated (%)	6	4-8
Oleic (%)	15-22	74-79
Linoleic (%)	72-79	11-19

The variant has the proportions of oleic and linoleic acids reversed from those of "normal" safflower. This has meant that a completely different technological type of safflower oil is available, one suitable for use as an edible oil. The reduction in iodine value appeared to be due to a single recessive gene.

Singh and Kumar (1948) found that *C. oxyacantha* had an iodine value of 112.8 with the fatty acid composition as follows: myristic 0.68 per cent, palmetic 3.11 per cent, stearic 3.62 per cent, oleic 55.8 per cent, and linoleic 36.81 per cent. Ghose (1916) reported an iodine value of 123.5. A sample with black seeds at Davis had a value of 141.0. Apparently *C. oxyacantha* is variable in this respect, and might prove a fruitful source of genes that affect iodine value.

C. Earliness

Safflower has been handicapped as a dryland crop because it is considerably later than the small grains. It blooms at Davis in early June,

when the small grains are being harvested. Under dryland conditions in California this means that safflower must advance from the bud stage to maturity without the benefit of appreciable amounts of rain. With abundant moisture in the soil this has not been a serious handicap, but on shallow soils or on deep soils with little reserve moisture the crop has suffered. For similar reasons (Table II) earlier maturity would be equally desirable in eastern Washington, northern Utah, and southern Idaho where safflower is grown. Earliness in terms of a shorter rosette period would make safflower more competitive with weeds. In Bombay state, where safflower is well established, earliness and a shorter rosette period are considered desirable (Argikar, 1950). Opinion in Greece is the same (Panos, 1956).

A nursery of introductions at Davis did not provide types appreciably earlier than N-10 (Table X). In Australia genes for earliness have been

TABLE X

Safflower Introductions Classified for Days to Bloom at Davis, California, 1957

	Days earlier (−) or later (+) than N-10						
Countries of origin	−10 to −7	−6 to −3	−2 to +2	+3 to +6	+7 to +10	+11 to +18	+19 to +26
India, Pakistan	13	59	127	49	11	2	
Iran, Afghanistan	—	—	—	2	3	2	1
Turkey, Syria, Israel	—	—	2	3	10	1	
Russia, Rumania	—	—	2	2	1	1	—
France, Spain, Portugal	—	—	6	1	—	—	—
Morocco, Algeria	—	—	3	1	2	—	—
Egypt, Sudan, Kenya, Ethiopia	—	—	7	8	10	2	—

found in introductions from Egypt, the Sudan, Syria, and Israel. Kupsow (1932) reports a range from 100 to 140 days in time to mature, with the ecotypes of Spain, Asia Minor, and India being extremely early. Crosses have been made at Davis between several early flowering varieties with the hope that still earlier types may be obtained by transgressive segregation.

D. Resistance to Rust

Rust (*Puccinia carthami* Cda.) has become a serious disease of safflower in the United States. The disease has spread rapidly because teliospores are carried on the seed and infect the germinating seedling. Seed

TABLE XI

Resistance of Safflower Varieties to Diseases

Variety	Origin	Root rots		Rust					Alternaria	
		P. drechsleri[a]	Pythium[b]	Race 1[c]	Race 2[c]	Race 3[d]	Nebraska[a,e]	Davis 1957	Leaf spot[a]	Bud rot[e]
N-1[f]	Turkey	R[h]	—	1[i]	1	4	S	—	VS	—
N-2[f]	Turkey	R	—	—	—	—	S	—	VS	—
N-3[f]		R	R	4	4	—	S	—	S	VS
N-4[f]	Turkestan	R	—	4	4	—	S	—	MR	—
N-5[f]	Afghanistan	R	R	3	3	—	S	S	MR	—
N-6	Egypt	MR	S	4	4	—	S	S	MR	MR
N-7	Turkestan	R	—	—	—	—	VS	—	S	—
N-8	Turkestan	R	R	4	4	4	VS	—	S	R
N-9	Sudan	VS	VS	4	4	—	VS	—	MR	VS
N-10	Egypt	S	VS	4	4	—	S	S	MR	—
N-852	Egypt	S	VS	—	—	—	S	S	MR	VS
Indian	India	S	R	4	4	—	VS	VS	S	VS
WO-14[g]	—	—	—	1	4	—	—	R	—	—
PACIFIC 1	—	—	—	1	4	—	—	MR	—	—
PACIFIC 2	—	—	—	1	4	4	—	MR	—	—
N-977-15-1	Rumania	—	—	1	1	4	R	R	—	—
N-977-16-1	Rumania	—	—	1	4	—	—	—	—	—
N-2555-4	France	—	—	1	4	—	R	—	—	—
N-2591-2-10	Morocco	—	—	1	4	—	R	—	—	—
780-3-3	—	—	—	0	3	0–4[j]	—	—	—	—

[a] Claassen (1949), Claassen and Hoffman (1950).
[b] Cormack and Harper (1952).
[c] Thomas (1955).
[d] Thomas (unpublished).
[e] Claassen (1952).
[f] From the variety Special Russian.
[g] Resistance from N-977-16-1.
[h] R = high resistance; MR = some resistance
S = susceptible; VS = very susceptible.
[i] 0 = necrosis or chlorosis without uredia.
1 = necrotic or chlorotic areas, a few with small uredia.
2 = necrotic or chlorotic areas, most containing small to mid-sized uredia.
3 = abundant, mid-sized uredia surrounded by chlorotic areas.
4 = uredia large and abundant with no necrosis or chlorosis
[j] 4 reaction on young leaves; 0–1 on old leaves.

treatments as used commercially have not been effective in killing all of the teliospores. Teliospores in or on the soil will infect susceptible safflower planted the following year. When near-isogenic varieties, one resistant to rust (WO-14) and the other susceptible (N-8), were grown under conditions of a rust epidemic, the yield of the susceptible variety was 65 per cent of the resistant, whereas under rust-free conditions the relationship was 95 per cent (Thomas, 1956). The pathology of safflower rust has been studied in some detail (Prasada and Chothia, 1950; Schuster and Christiansen, 1952; Thomas, 1952b; Sackston, 1953; Calvert and Thomas, 1954; Schuster, 1956; Daly and Sayre, 1957; and Daly *et al.*, 1957) but it will not be reviewed further here.

When safflower materials were first rated for infection by rust (Claassen, 1949, 1952), it appeared as if resistance might be available from a number of areas; introductions from Turkey, Rumania, France, and Morocco gave selections with resistance (Table XI). The same race or races of rust probably were present in the nursery at Davis in 1957 (Table XII), since the same areas provided resistant types.

TABLE XII

Safflower Introductions Classified for Resistance to Rust at Davis, California, in 1957

Country of origin	Number of introductions	Introductions with some resistant plants[a]
India, Pakistan	264	199,952; 214,150
Iran	9	195,472; 222,240; 227,502; 53-3
Afghanistan	4	220,283; 220,647
Turkey	16	170,274; 175,624; 210,460
Syria, Israel	7	181,866; 209,281; 226,993
Russia, Rumania	6	Early Russian; 209,286; 209,287
France, Spain, Portugal	7	198,844; 198,845; 210,834; 56–16
Morocco, Algeria	6	195,895; C2–3AF2; C4BAF2
Kenya	8	209,295 to 209,297; 209,301
Sudan	10	193,474; 193,475; 193,764; 193,765
Ethiopia, Africa	10	194,913; 195,925; 209,289

[a] P. I. numbers with six digits; University of California introductions hyphenated; and balance with the name or number in the country of origin.

The high level of resistance in N-977-16-1, which was incorporated into WO-14, failed against a race of rust from California (Thomas, 1955). This resistance was due to a single dominant gene (Claassen, 1952). The situation was the same in California when WO-14 was crossed to N-10 and Australian Spineless (Table XIII); the F_1 was resistant, and about three-quarters of the F_2 were resistant or showed a trace of rust. Susceptible F_2

TABLE XIII

Segregation of F_2 Populations of Safflower for Resistance to Rust at Davis, California, 1955

Parent or cross	Number of plants: Rust free	Trace	Suscep- tible	P value for fit to 3:1 ratio[a]
N-10	--	—	6	--
Australian spineless	-	--	10	—
WO-14	13	—	—	--
N-997-15-1-3	10	--	—	—
N-10 × WO-14	101	15	25	0.05–.01
Aust. spineless × WO-14	48	14	20	0.90–.80
N-10 × N-997-15-1-3	63	34	39	0.50–.30

[a] Rust-free and trace classes combined.

plants bred true for susceptibility in all cases; F_2 plants with a trace of rust usually yielded progenies that segregated; and resistant plants gave progenies that bred true for resistance or segregated in a ratio of three resistant to one susceptible.

The level of resistance in N-977-15-1 was not so high as in N-977-16-1 in western Nebraska (Claassen, 1952) and in the nursery at Davis in 1956. Resistance was found to be due to a single dominant gene (Table XIII) which behaved in inheritance very much like the gene for resistance in N-977-16-1. The genes may not be the same because N-977-16-1 is susceptible to Race 2 and N-977-15-1 is resistant (Table XI).

Thomas has identified three races of rust. Race 3 (Table XI) appears to be pathogenic to all commercial varieties and to all sources of resistance to Race 2. Only one line, 780–3–3, has resistance to this race, and that in the mature plant stage only. Thomas found that races 1 and 3 were prevalent in California in 1955, 1956, and 1957. Race 2, although found in California in 1954, has not reappeared since. The development and spread of new races of rust makes it imperative that a search be made for additional sources of resistance to the separate races. It is imperative also that more be learned about the inheritance of resistance to the separate races, this to facilitate the combination of these genes in one variety.

There have been trials of several seed treatments in an effort to kill all of the teliospores on the seed, but without too much success. Any treatments, when repeated or when used on a commercial scale, permitted a few spores to survive. Thomas (unpublished data) has found that the

volatile mercuric compounds have been superior, apparently because they reach the spores lodged in cracks in the seed coat. Higher temperatures promote volatility, and Thomas was able to get perfect control if the dosage of Panogen, Ceresan 100, and Ceresan M was 4 ounces per bushel, and the seed was stored in sealed containers at 30° C. for 3 days after treatment.

E. Resistance to Root Rot

In most cases in California and Nebraska, where root rot has attacked safflower, it has been caused by *Phytophthora drechsleri* Tuck. (Thomas, 1951 and 1952c; Erwin, 1950). In California it was severe in 1950, when most of the acreage was under irrigation. It has appeared in all areas when safflower has been surface irrigated, being particularly severe where water stands for even short periods of time. Because the better safflower varieties are susceptible, the production of safflower in irrigated areas has been prohibited almost entirely. Some varieties do have resistance (Table XI), and Thomas and others have been able to transfer resistance through backcrossing to N-10 types (personal communication). The better of these will be under test in 1958 in areas particularly subject to root rot.

Root rot caused by Pythium has been severe under irrigation, but not under dryland (Cormack and Harper, 1952). It may be significant that all of the varieties resistant to this disease (Table XI) came from Africa. No breeding program appears to be concerned with this disease.

Rhizoctonia solani Kuehn. and a species of Fusarium have been found on the roots of safflower (Litzenberger and Stevenson, 1957), but not in amounts sufficient to encourage the development of resistant varieties.

F. Resistance to Other Diseases

Botrytis blight, or gray mold, caused by *Botrytis cinerea* Pers. has been abundant on safflower whenever it is grown in coastal areas subject to fog. It has also been observed in the Sacramento Valley whenever unseasonal rains have occurred when safflower has been in the late bud stage or in bloom. The disease attacks the entire head and invades the receptacle so that the head lifts off easily. Scheibe (1938) has reported resistance to this disease in introductions from Rumania. In a small nursery of 16 safflower varieties grown in coastal California, two introductions from Rumania did show more resistance than most materials, but one introduced (P.I. 209,290) from Egypt appeared to be highly resistant. Varieties from India and N-10 were particularly susceptible. Resistance to this disease should extend considerably the area of adaptation of safflower.

Leaf spot caused by *Alternaria carthami* has been reported as one of the most serious diseases of the western part of the northern Great Plains

(Claassen and Hoffman, 1950). It has been particularly severe in irrigated plantings during July and August following heavy dews or frequent showers (Claassen, 1949). The disease may be seed transmitted to cause seed rot and damping off of seedlings. This phase of the disease may be controlled by seed treatment with mercuric compounds (Thomas, 1952a). To the writer's knowledge no directed effort is being made to develop varieties resistant to this disease, though Thomas (1950) reported that N-9 and six other selections were highly resistant.

Verticillium wilt has been found on safflower in Australia (Purss, 1956), and has been seen a number of times in California. It has not been found at Davis in amounts sufficient to rate varieties for their relative resistance.

G. Resistance to Insect Pests

In the areas of the Old World where safflower or its wild relatives are indigenous, insects have been a serious problem (Bytinski-Salz, 1954; Knowles, 1955). Apparently insect pests of wild safflower and other composites have moved into commercial fields. Although no parts of the plant have been immune, insects attacking the heads have been the most serious. Of the latter, the larvae of the safflower fly (*Acanthiophilus helianthi* Rossi) has been perhaps the most damaging, and has been an important factor in eliminating safflower as a commercial crop in France. No resistance to the safflower fly has been reported.

Aphids have been a problem in areas where safflower has been introduced. Dusting or spraying to control this insect has been necessary occasionally in California. Although resistance to this pest would be desirable no resistant variety has been reported. No variety has been found resistant to Lygus (*Lygus* spp.), an insect that is frequently found in late sown safflower in California.

H. Frost Resistance

Klages (1954) reported that varieties had different levels of resistance in the seedling stage to damage from frost. Varieties showing an average resistance rating of 9.0, on a scale of 10 (no damage) to 3 (severe damage) were P.I. Nos. 182,165; 183,669; 175,624; 174,081; 177,302; all from Turkey, and C.I. No. 2377 from the U.S. Department of Agriculture. Varieties with resistance to frost were highest in yield. Where frost damage has occurred to safflower in the seedling stage in California, it has been more severe on varieties that were growing or elongating rapidly; N-852 suffered more than N-8. Frost resistance, if it could be achieved in a rapidly growing variety, would be a distinct improvement. It would permit earlier plantings in the northern Great Plains, where the length of the growing season is an important limiting factor.

I. Spinelessness

It has been hoped that a spineless variety might be developed with all the best attributes of those that are spiny. To date no such variety is available in spite of considerable work in this direction. There is need for more research to determine whether the gene or genes for the spineless character are linked with undesirable genes or whether they have some adverse pleiotropic effect.

J. Yield

Argikar *et al.* (1957) has studied within six varieties the relationship of many morphological and physiological characters to yield. As would be expected, yield was positively correlated with size of head, number of branches and heads, and spread of the plant. When different varieties were compared, no correlations were computed to show the relation between yield and plant characters.

Most efforts in breeding programs at the present time in the United States has been through backcrossing to add genes to existing varieties, principally N-10, to remedy defects. This has been in terms of additions of resistance to root rot, resistance to rust, and earliness. In other words the yielding ability of N-10 appears to be satisfactory, if it can be protected from the hazards that affect its production.

K. Varieties

All successful and high yielding safflower varieties in the United States have been developed by Dr. C. E. Claassen and his associates. When he was at the University of Nebraska, these bore the prefix "N." Since being associated with commercial companies in California, they have had the prefix "WO" or "PACIFIC." The variety that has been most widely grown in the United States and California is N-10. PACIFIC-1, which is replacing N-10 in California, was developed from N-10 by adding to the latter the gene for rust resistance in WO-14. N-6, a variety that was grown in preference to N-10 under irrigation, will follow N-10 and PACIFIC-1 in importance. It is interesting to note that all of these successful varieties stem from introductions brought in from Egypt. In Australia the most successful materials have originated from N-803, the same material from which N-6 was obtained. Klages (1954), however, found that the introductions from Turkey, P.I. 182,165 and 183,669 were higher yielding than other varieties at Moscow, Idaho, and among the better yielding varieties at Twin Falls in the same state.

In spite of the large number of introductions that have been obtained from India, none of them have been promising in California or the United

States. Part of this stems from the fact that they have been lower in oil than other introductions, and part from the fact that practically all of them have been extremely susceptible to rust. On the other hand, no report has been received from India stating that introduced varieties have been more successful than indigenous ones. It would appear that there is an important difference between the environments of California and India, such that widely different types are favored in the two locations.

Because some selections of safflower have shown a large amount of natural crossing, and because some of these hybrids have shown marked heterosis, there has been some interest in developing hybrid varieties. Although the U.S. Department of Agriculture has some work progressing in this direction, it is unlikely that a hybrid variety will be forthcoming for some time.

L. Irradiation

There appears to be little work underway with a view to inducing mutations in safflower through irradiation. Beard (1955) found that thermal neutrons were more effective than X-rays on barley and mustard seeds than on those of maize and safflower. One roentgen of X-ray was biologically equivalent to 2.65×10^9 thermal neutrons per cm.^{2} on safflower seeds. He believes that about 20,000 roentgens of X-rays or 33.8×10^{12} thermal neutrons per cm.^{2} will reduce plant height in the seedling stages about 50 per cent, and give a stand of 40 to 60 per cent.

M. Personnel in the United States

Dr. C. E. Claassen is developing varieties adapted to California, having in mind increased yield, a higher oil content, and greater resistance to disease. Formerly with the University of Nebraska, he is now President of the Pacific Oilseeds Company in Woodland, California. Dr. J. H. Williams, now at the University of Nebraska, is working toward varieties that are higher yielding, high in oil, resistant to disease, and early. He is studying the inheritance of, and factors affecting, oil content. His work in western Nebraska is done in cooperation with Mr. W. F. Peterson of the U.S.D.A. at the Scottsbluff Field Station. Mr. Peterson is interested primarily in developing better cultural practices. Dr. Wade Parkey of the U.S.D.A., who is at the State College of Agriculture, Logan, Utah, feels that future varieties should be earlier and resistant to both rust and root rots. At the University of Arizona in Tucson Dr. D. D. Rubis is developing varieties resistant to root rots, higher in oil, and earlier. He has made some progress in developing hybrid varieties. The University of California is studying the inheritance of a number of characters including resistance to rust. The

relationships of cultivated safflower to the wild species are also being investigated.

Pathologists have made significant contributions toward an understanding and control of safflower diseases. Those actively working on safflower at the present time are: Dr. C. A. Thomas, Industrial Crops Section, U.S.D.A., Beltsville, Maryland; Drs. M. L. Schuster and J. M. Daly at the University of Nebraska; and Dr. B. R. Houston and Mr. K. E. Mueller (U.S.D.A.) at the University of California.

VIII. Conclusions

Advances in the status of safflower in the United States have been achieved in a large part by the plant breeder. He has found types some 20 per cent higher in oil than those available fifteen years ago. During the same period yields have been improved an equal amount. Actually these spectacular increases have been made simply by selecting among a rather limited supply of introductions from the areas where safflower is indigenous. There would seem to be a real need for more collections of safflower from abroad, a need to expand the pool of germplasm in the United States and in other countries where safflower has been introduced. It is to be hoped that collections of the wild species may be obtained also, since they may provide genes that are not available from the domestic species. The plant breeder needs more building material for present and future varieties. The diseases that afflict the crop and limit its area of adaptation are rust, root rots, and leaf blights. These diseases present problems that must be solved in large measure by the plant breeder. He may have to modify the seed size, the seed shape, and the time it takes the crop to mature. The plant breeder cannot forget his basic research. There is a need for more studies into the inheritance of disease resistance, earliness, yield, and oil content. The evolution of the species from wild types should be charted to give direction to future changes.

Perhaps because the plant breeder has played an important role in the development of safflower, there has been some neglect of production research. Further inquiry should be made into the reasons why safflower does well in one location and not in another. Even such elementary items as depth of seeding, rates of seeding, row spacings, and dates of seeding need additional research, and particularly so with the development of new varieties. Better methods of treating seed may reduce rust to a minor factor in safflower production. Research into weed control, irrigation, and fertilization is necessary. Limited research has indicated that safflower oil has many valuable attributes, both as an edible and an industrial oil. Additional research should uncover other possibilities.

Safflower is a crop that has adjusted itself rather easily to American agriculture. In the main it has been a substitute for cereal crops in western areas, and it has been adaptable to planting and harvesting with their equipments. The oil has found a ready market and the meal, though somewhat high in fiber, has been used as a livestock feed. Safflower would seem to occupy a permanent place in this nation's economy.

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REACTIONS OF AMMONIA IN SOILS

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I. Introduction

Use of ammonia as a source of nitrogen for agronomic application has become widespread in recent years. Ammonia is used as a gas, anhydrous ammonia, or in aqueous solutions sometimes containing other materials as well. Ammonia is also a product of microbial activity in soil.

Several writers have reviewed certain aspects of nitrogen in its connection with soils. Andrews (1956) and Andrews *et al.* (1951) have discussed and considered some of the more practical aspects of the use of anhydrous ammonia in fertilizer application. Harmsen and Van Schreven (1955) discussed the mineralization of organic nitrogen in soil. Broadbent (1953) and Bremner (1954) reviewed recent work on soil organic matter.

The fixation of the ammonium ion by clay minerals is a subject which has been receiving considerable attention. Gieseking (1949) and Reitemeier (1951) have discussed some of the literature concerning this subject. Meiklejohn (1953) has reviewed literature concerned with the biological oxidation of ammonia.

Reactions of ammonia in soils cannot, of course, be completely divorced from the reactions of the ammonium ion in soil. However, perhaps some distinction should be made in discussing these forms of nitrogen. Ammonia is an electrically neutral but highly polar molecule, whereas the ammonium ion possesses an electropositive charge and exhibits properties similar to those of other cations in solution. Many writers use the term "ammonia" to refer to ammonia or the ammonium ion interchangeably. Since many of these papers are concerned with the use of ammonium salts, it appears to the author that the term "ammonia" in such cases may be a misnomer. In alkaline soils and where anhydrous ammonia or aqueous solutions of ammonia are used, the concentration of ammonia may be quite high in comparison with that of the ammonium ion. For instance, a 1 M solution of ammonia in water at 25° C. is only 0.00426 M with respect to the ammonium ion. This review is concerned primarily with reactions of ammonia, with some discussion of the ammonium ion especially in its relationship to the ammonia molecule. The subjects of biological nitrification, mineral fixation, exchange reactions, and other properties of the ammonium ion are left primarily to other reviews.

II. Mechanisms of Ammonia Sorption

Ammonia may be sorbed on colloidal systems by chemical or physical mechanisms or a combination of these. The most fundamental difference between the two lies in the forces involved. The forces concerned with physical sorption are similar to those in condensation phenomenon, whereas the forces in chemical sorption are similar to those active in chemical reactions. Chemical sorption of ammonia by a colloid is characterized by difficulty in reversing the reaction, high heat of sorption, and specificity with respect to the nature of the adsorbent. Physical sorption of ammonia is characterized by easy reversibility, comparatively low heat of sorption, and nonspecificity with respect to the nature of the adsorbent.

A. Chemical

Chemical sorption by soils is expected where hydrogen ions (or hydronium ions) are present with the resulting formation of the ammonium ion. This reaction occurs wherever there is a source of hydrogen ions (H^+). The H^+ ions may arise from the soil solution or the solid phase. In

the case of hydrogen ions provided by the soil solution, an ordinary chemical reaction takes place to form either a salt or ammonium hydroxide. In the case of the reaction of ammonia with hydrogen ions associated with clay minerals and organic matter, the ammonium ion is also formed but in an association with these materials. The most common locale of labile H^+ ions on clay minerals and organic matter is at cation exchange sites. Upon reaction of ammonia with these hydrogen ions, ammonium ions become the exchangeable ions.

The reaction of ammonia with active H^+ ions provided by carboxyl and phenolic groups in soil organic matter is likewise expected. In addition to this type of reaction with organic matter ammonia may react with active organic groups to form covalent chemical bonds and give such organic nitrogen compounds as amides, imides, and amines.

B. Physical

Physical sorption of ammonia by soils is nonspecific in that the presence of H^+ ions is not required. It involves lower sorption energy than the chemical sorption and therefore is more easily reversible. Purely physical sorption of ammonia on charcoal has been observed by Titoff (1910). The ammonia molecule is a great deal like water in its properties and reactions. The molecule is tetrahedral in shape with the nitrogen atom at one corner and hydrogen atoms at each of the three other corners. It is logical to assume that upon sorption on the surface of a clay, a hydrogen bond may exist between the hydrogens of the ammonia molecule and the oxygen atoms on the surface of the clay. This is analogous to the proposed mechanisms for the sorption of water by clays described by Gieseking (1949). It is well known that ammonia can form "hydrates" with various salts, such as $CaCl_2{-}2NH_3$, similar to genuine hydrates. It is possible that ammonia may form such "hydrates" with exchangeable bases in the exchange complex of soils.

Where a supply of H^+ ions or active organic groupings are provided by an adsorbent, one may expect both chemical and physical sorption to occur. The chemical sorption would proceed first because of its greater reaction energy and would continue until all chemically active sites had reacted. Physical sorption would then occur as the pressure was increased.

III. Reactions of Ammonia with Soil Constituents

A. Clay Minerals

Chemical sorption of ammonia by H^+ saturated clays was observed by Buswell and Dudenbostel (1941) who noted that ammonia reacts with H^+ saturated clay to form ammonium saturated clay. Cornet (1943)

found that the sorption of ammonia by H^+ bentonite was accompanied by an increase in the *c* axis spacing, indicating sorption on interplanar surfaces of the bentonite. He also found that upon attempting desorption of the ammonia, some could not be removed. He proposed a reaction between the exchangeable H^+ ions and ammonia to form the ammonium ion which then occupied an exchange position on the colloid. It is also likely that the ammonia may neutralize hydrogen ions provided by hydrolysis of aluminum ions which in turn are held at cation exchange sites on the mineral. Jenny *et al.* (1945) found that sorption of ammonia in aqueous solution by kaolinite was a function of the pH of the solution while sorption by montmorillonite was constant, irrespective of the pH of the solution.

In studying the properties of bentonite partly saturated with H^+ ions and partly with NH_4^+ ions, Cook (1935) found that heating at 450° C. for 48 hours produced a H^+ saturated clay. Several other workers have also studied the thermal decomposition of ammonium saturated minerals. Bottini (1937a, b) found ammonia to be volatilized at high temperatures from ammonium saturated clays. The energy required to dissociate ammonia from the clay mineral was found to depend on the nature of the association of the ammonium ion with the mineral. He found that ammonium ions bound in the intermicellar spaces of the clay resisted thermal splitting to a greater degree than those sorbed on the external surface of the clay. Another interesting finding of Bottini (1937b) was that a mixture of ammonium calcium clay began to decompose at higher temperatures than pure ammonium clay. Cornet (1943) concluded that the site of the ammonium ions on the clay determined the temperature at which they were decomposed. Working with ammonium saturated bentonite, he concluded that temperatures up to 125° C. decomposed ammonium ions on the broken bond surfaces, whereas decomposition at higher temperatures was due to ions in the exterior planar and interplanar surfaces. Barshad (1948) found that little ammonia was lost from ammonium saturated vermiculite below 550° to 600° C. when all the ammonium ions were decomposed to ammonia. Scott *et al.* (1956) studied the decomposition of ammonium ions adsorbed on kaolinite, illite, bentonite, and vermiculite and found that it occurred over a wide range of temperature. They found the temperature of decomposition to be influenced by the nature of the exchange site and by the entrapment of ammonium ions in the mineral lattice. They concluded that fixed ammonium ions resisted thermal decomposition more than exchangeable ions but that no sharp distinction could be observed between the two forms. The work on thermal decomposition of ammonium saturated clays may be thought of as investigations involving the desorption of chemically sorbed ammonia. Most of this work indicates that ammonia chemically sorbed by clay minerals does not exist at a single energy

level but that a wide range exists in the energy of chemical sorption of ammonia by clays.

The neutralization of labile H^+ ions on clay minerals does not appear to account for all of the chemically sorbed ammonia. Mortland (1955) found that some ammonia was irreversibly sorbed by calcium saturated bentonite, a system in which labile H^+ ions were presumably not present. Large parts of the United States are occupied by soils neutral or alkaline in reaction, yet losses of ammonia from anhydrous ammonia when properly applied appear to be small indicating a strong sorption by soils which do not provide a high concentration of H^+ ions.

The physical sorption of ammonia by clays and clay minerals has been demonstrated by Jenny *et al.* (1945) and Mortland (1955). This was established by the easy reversibility of sorption, and the lower energy of sorption compared to chemical sorption. Jenny *et al.* working with H^+–Yolo clay demonstrated both chemical and physical sorption when they were able to remove, merely by aeration, a portion of the sorbed ammonia. Mortland and Erickson (1956) showed the nonspecificity of ammonia sorption by a group of different base-saturated clay minerals. This was indicated by a linear relationship between the value for a monolayer of ammonia gas, Vm, obtained from the Brunauer, Emmett, and Teller equation, and the amount of sorption at given relative pressures. If different clay minerals sorbed ammonia by different mechanisms, such a relationship would not likely be obtained. The effect of exchangeable cations on ammonia sorption by bentonite was found to follow the order $H > Ca > Na > K$. The fixation of potassium by the bentonite particularly reduces the sorption of ammonia.

Sorption isotherms of ammonia on base-saturated clays have been utilized by Mortland (1955), Zettlemoyer *et al.* (1955) and Mortland and Erickson (1956) for the determination of specific surface. Upon application of the Brunauer, Emmett, and Teller equation to this data specific surface figures could be obtained. Other workers have applied this equation to sorption isotherms of nitrogen, ethane, and water on clays. In the case of nitrogen, small specific surface figures were obtained for montmorillonite, indicating that the nitrogen was not penetrating the interlayer surfaces. Upon use of ammonia, large specific surface figures were obtained indicating that this highly polar molecule is capable of penetrating the interlayer surfaces of montmorillonite. Mortland (1955) obtained a specific surface value for calcium saturated Wyoming bentonite of 572 m^2 per gram while Zettlemoyer *et al.* (1955) obtained a value of 556 m^2 per gram for natural Wyoming bentonite.

The effect of temperature on the sorption of ammonia by calcium bentonite was studied by Mortland (1955). The amount of ammonia sorbed

decreased with increasing temperature. The heat of sorption of ammonia on calcium saturated kaolinite and montmorillonite was reported. Little difference was found in the heat of sorption calculated from the Brunauer, Emmett, and Teller equation: 6500 calories per mole for kaolinite, and 6330 for montmorillonite. These figures represent the average heat of sorption on the least active portions of the surface of the adsorbent when a monolayer of ammonia molecules is almost complete. Heat of sorption was calculated from sorption isotherms on calcium montmorillonite obtained at different temperatures using the Clausius-Clapeyron equation, an application of thermodynamic theory. A wide variation in heat of sorption was obtained depending upon the amount of clay surface covered. Heat of sorption decreased as ammonia was sorbed. The heat of sorption values ranged from about 24 kilocalories per mole when the clay surface was 20 per cent covered with ammonia molecules to about 13 kilocalories per mole when the surface was 80 per cent covered with ammonia molecules. These heats of sorption are of the same order as those obtained for ammonia on zeolites by other workers and summarized by Marshall (1949).

The ammonium ion may enter into fixation reactions with certain clay minerals in a manner similar to potassium fixation. The word "fixation" refers here to a condition wherein the ion cannot be exchanged with other cations under the ordinary conditions of cation exchange. Gieseking (1949) and Reitemeier (1951) have reviewed work on the fixation of the ammonium ion by clay minerals. Once ammonia has reacted with a proton it becomes the ammonium ion. Ammonia therefore may ultimately be fixed by clay minerals in unavailable forms by the same processes that render the ammonium ion of salts fixed and unavailable. The clays which may be involved in such fixation reactions are illites, montmorillonite, and vermiculite. Sohn and Peech (1957) found that the mineral fraction of some New York soils fixed appreciable amounts of nitrogen supplied as ammonia. Stevenson (1957) reporting on the changes in fractional distribution of nitrogen associated with the narrowing of the C:N ratio with depth in the soil profile suggests that a portion of the nitrogen in soils is in the form of the ammonium ion, irreversibly fixed to clays. Rodrigues (1954) found in some tropical soils a considerable amount of ammonium nitrogen fixed or rendered resistant to extraction by combination or association with clay minerals. Evidence seems to accumulate that there is in many soils an inorganic form of nitrogen, probably the ammonium ion, which is resistant to extraction and is probably combined with clay minerals in a nonexchangeable form.

B. Organic Matter

Several workers have found that a large portion of the ammonia sorbed by organic matter of various kinds is in a nonexchangeable form, and is in

fact quite resistant to decomposition. Ehrenberg and Heimann (1930) obtained a patent on a process by which they fixed ammonia in peat in the presence of oxygen and various catalysts. They were able to raise the nitrogen content to 15 per cent. Kalb *et al.* (1931) observed the uptake of ammonia by lignin and that some could not be removed upon exposure to the air. Feustel and Byers (1933) reacted ammonia with peat and found that only a fraction of the total nitrogen combined in the peat was ammoniacal in form. Lignin, sulfite waste liquor, and soil organic matter were found to increase in nitrogen content upon reaction with ammonia. From their data these workers concluded that there was no relationship between the amount of nitrogen originally present and that taken up in the treatment with ammonia. Scholl and Davis (1933) also studied reactions between ammonia and peat. Their data concurred with that of the other workers in the observation that most of the nitrogen fixed was not in the ammonium form. They did not observe a relationship between pH of the peat and the amount of ammonia sorbed. They attempted to determine the amounts of the different forms of nitrogen present in an ammoniated peat from Michigan with the results shown in Table I.

TABLE I

Nitrogen Content of Ammoniated Michigan Peat

Form of nitrogen	Amount present (%)
Kjeldahl (total)	11.13
Ammonium	1.33
Amide	1.12
Imide	2.57
Other	6.11

Relatively little is known about the exact nature of the ammonia-organic matter complex, or its susceptibility to microbial attack. The latter point is important from the standpoint of its availability for plant use. However, knowledge of the reactions of ammonia with known organic groups should give an insight into its possible reactions with soil organic matter. The fact that ammonia will react with carboxyl, phenol, aldehyde, ketone, and alcohol groups to form amines, amides, and imides of various kinds suggests the possibility of a variety of reactions with soil organic matter.

Junker (1941) observed that ammonia combined with lignin in three different stages, two of which might correspond to the combination with phenolic hydroxyl groups, the third with an aldehyde or alcoholic hydroxyl group. He also observed the uptake of oxygen by the lignin sol but did not relate it to ammonia sorption.

Mattson and Koutler-Andersson (1941, 1942, 1943, 1954a and b, and 1955) have reported extensively on the reactions of ammonia with peat, litter residues, humus, lignin, and organic compounds of known composition. In reacting these materials with aqueous solutions of ammonia, they found a chemical fixation of ammonia in nonexchangeable forms. The amount of fixation in nonexchangeable form was found to be proportional to the acidoid content (Mattson and Koutler-Anderson, 1941). They reported that the fixation of ammonia strengthened the basoid groups resulting in an increase in pH and isoelectric point. This was explained as the result of the formation of an inner salt (zwitter ion) which reduced the apparent strength of the acidoids. They observed (Mattson and Koutler-Andersson, 1942) that fixation of ammonia was associated with a simultaneous oxidation reaction. The oxidation process and, therefore, ammonia fixation was favored by an alkaline reaction. The oxidation status of the organic material was then observed to have a direct effect on its ammonia fixing capacity, since accomplished oxidation was observed to suppress and simultaneous oxidation to favor fixation of ammonia. Mattson and Koutler-Andersson (1942) concluded that ammonia was initially bound by an intermediate oxidation group, possibly a carbonyl group. They considered the ammonia fixing group to be fairly stable since it exists in natural materials, and that the bond between the ammonia and the reactive group was very stable since it resisted chemical oxidation and acid hydrolysis. Strong alkali removed nearly half of the fixed ammonia. Later, Mattson and Koutler-Andersson (1943) studied ammonia fixation by organic compounds of known constitution and obtained a wide variation in the amount of fixation. Oxidative ammonia fixation was found to be a property of di- and tri-atomic phenols and of polyatomic-phenolic acids such as gallic and tannic acid as well as of lignin and of the water and alcohol soluble organic matter of plant and humic materials. They suggested that the oxidative fixation of ammonia by lignin was by way of the phenolic hydroxyl groups with ultimate incorporation of the nitrogen in a ring structure. However some evidence was presented which indicated a nonoxidative type of fixation of ammonia, particularly by glucose. Bennett's (1949) data, from his methylation studies of lignin, seem to support Mattson and Koutler-Andersson's idea that simultaneous oxidation and ammonia fixation takes place by way of the phenolic hydroxyl groups.

Laatsch (1948) and Laatsch *et al.* (1950, 1951) do not agree entirely with Mattson and Koutler-Andersson in allocating most of the nitrogen in humus to fixation reactions with ammonia. These authors give two ways in which humus can arise in the soil: first, a combining of lignin and products of hydrolysis of proteins under appropriate conditions; second,

oxidative ammonia fixation by quinoid products of metabolism of molds and actinomyces, assuming a suitable source of ammonia.

Mattson and Koutler-Andersson (1943) compared fixation by beech leaf humus of ammonia from water solution and the gaseous state. The material fixed 4.00 per cent nitrogen from the aqueous solution and 3.44 per cent from the gaseous phase. Beech leaf lignin fixed 3.64 per cent nitrogen from ammonia in the gaseous phase produced in a separate container by the action of bacteria on urine and dung. They also investigated the fixation of the exchangeable ammonium ion by humus and found that the amount of fixation decreased rapidly on the acid side. Where 50 milliequivalents (meq.) of the ammonium ions were present per 100 g. of humus in water solution, only 2.3 meq./100 g. were fixed at a pH of 6.97. When suspended in a 1 *N* KCl solution and with autoxidation for 7 days, only 0.8 meq./100 g. were fixed at pH 5.40. This suggests an important difference in the fixation of nitrogen in soil organic matter as a function of the nature of a nitrogen fertilizer. In the application of ammonium salts to acid soils relatively little nitrogen may enter into the fixation reaction with organic matter, but in the use of anhydrous ammonia or aqueous solutions of ammonia, fixation might be expected to be much greater due to the more alkaline pH in the region of such fertilizer application. Since ammonia fixed by organic matter is very stable, according to Mattson and Koutler-Andersson, one might expect such nitrogen to be only slightly available to microorganisms and plants. Comparative experiments on the relative availability to crops of nitrogen from salts and from anhydrous ammonia or aqueous solutions of ammonia, when applied to soils high in organic matter or organic soils, should determine whether this fixation reaction is important in removing ammoniacal nitrogen from the available category. No such difference in availability between nitrogen fertilizers on organic or mineral soils has been observed at the Michigan Experiment Station. However, the observation has been made that fall application of anhydrous ammonia, ammonium nitrate, or urea to organic soil has seldom resulted in crop response the following year. Early spring application of these fertilizers has not been as effective as side-dressings, during seasons of good response to nitrogen. Whether chemical fixation, leaching following nitrification, or some other process is responsible has not been determined.

Mattson and Koutler-Andersson (1954b) concluded that lignin is the chief if not the only constituent involved in autoxidation and that it is the chief constituent of organic matter responsible for ammonia fixation.

Mattson and Koutler-Andersson (1954a, 1955) suggest that peat can be expected to obtain most of its nitrogen by direct sorption of ammonia

from air. In their work on peat soil they found a functional relationship between the sum of the original and fixed nitrogen and the lignin content. They also observed a complementary relationship between original nitrogen content and the amount of nitrogen fixed from ammonia. Where one was high the other was low and vice versa. The sum of the original nitrogen content and the nitrogen fixed from ammonia is with few exceptions close to a value of 8 per cent. They concluded that the lignin in peat is more or less unsaturated with nitrogen and ammonia fixation is a measure of its unsaturation. This is at variance with the work of Feustel and Byers (1933), who found no relationship between the amount of nitrogen originally present and that taken up in treatment with ammonia. The chemical analyses of Mattson and Koutler-Andersson indicate that recent peats have a greater original nitrogen content than older deposits. This they attribute to the presence of higher concentrations of ammonia in the air from the burning of fossil fuels.

Exact information on the position of nitrogen in the structure of humic substances is still to be obtained. Stevenson (1957) suggests that the evidence for the presence of lignin-ammonia complexes in the soil is presumptive and that there is no proof that large quantities of soil nitrogen occur in this form. His data showed an increase in the proportion of total nitrogen released by acid hydrolysis as ammonia, and a decrease in the proportion of acid-insoluble nitrogen with depth in the soil. He suggests that if ammonia-lignin complexes were present in large amounts, they would have been manifested by higher values for acid-insoluble nitrogen and lower values for ammonia nitrogen than he obtained. Although the evidence for the presence of lignin-ammonia complexes in natural soils is not direct, it appears to the author that their formation may be expected when fertilizer nitrogen is applied to the soil particularly in the form of anhydrous ammonia or aqueous solutions of ammonia, or materials such as urea which release ammonia rapidly by hydrolysis in the soil. It should be pointed out, however, that this statement is based on laboratory data and that to the author's knowledge no data have been published showing the actual formation of these complexes upon application of fertilizer materials in the field. The availability of such fixed nitrogen to plant growth is a subject in need of investigation. Some preliminary work by Johnston (1957) indicates that the availability to microorganisms of nitrogen fixed in resistant combinations with lignaceous materials in humus depends on the presence of other more available energy substrates which may hasten the decomposition of native soil organic matter and increase the rate of release of the fixed nitrogen.

There is evidence that nitrogen may be chemically fixed by lignin from forms other than ammonia. Bremner (1952) found that nitrogen content

of wood lignin was increased from 0.08 per cent to 3.6 per cent after contact with nitrous acid at room temperature for a few hours. The nitrogen fixed from nitrous acid was found to be remarkably stable to hydrolysis with acid or alkali. Bremner and Shaw (1957) studying the properties of lignin-ammonia complexes found they were very resistant to decomposition. The decomposition of nitric and nitrous acid treated lignin was somewhat more rapid. Voigt *et al.* (1949) reported that growth of black locust seedlings and buckwheat was benefited when grown in sandy soil mixed with compost which had been treated with ammonia in comparison with untreated compost. No characterization was made of the nature of the nitrogen in the compost before or after treatment.

It is evident from the previous discussion that ammonia may be chemically sorbed by organic matter in a fairly stable condition. Little is published on the fertility aspects of this problem or its agronomic implications. Relatively little is known about the amount of nitrogen chemically fixed by organic matter when nitrogen fertilizers of various kinds are added to soils. Although it is known that ammonia can be chemically fixed by organic matter, more information is needed about the availability of this fixed nitrogen to microorganisms and plants.

IV. Nonbiological Oxidation of Ammonia

The oxidation of ammonia may take place by chemical, photochemical, or biological processes. In the presence of appropriate catalysts and at high temperatures and pressures, ammonia may be oxidized chemically to nitrate. Rossi (1933) indicated that nitrates were produced by a physicochemical reaction in the uppermost layer of soil in contact with the air. He based his conclusion on the observation that nitrates were produced at high temperatures (30–55° C.), independent of biological activity, after the nitrites and nitrates were leached out. Waksman and Madhok (1937) have reviewed the subject of nonbiological oxidation of ammonia and suggest other possibilities for explaining this data, such as the possibility that nitrates already present in the soil were incompletely removed by leaching. Also biological oxidation of the ammonium ion is known to occur at temperatures up to 40° C., as found by Panganiban (1925), and at 35° C. by Fredrick (1956).

Considerable work, reviewed by Waksman and Madhok (1937) shows that ammonia may be oxidized to nitrites by a photochemical process. Berthelot and Gaudechon (1911) demonstrated that ammonia can be oxidized photochemically. Rao and Dhar (1931) found ammonia was oxidized to nitrites by sunlight in the presence of suitable catalysts. Several workers have suggested such a process at the soil surface, while others

have failed to observe such a reaction. Rigg *et al.* (1952) showed that ammonia in dilute basic aqueous solutions could be oxidized to nitrite at room temperature by the action of free radicals produced by irradiation with X-rays, provided oxygen was present. Since such radiations as X-ray and sunlight, widely separated on the electromagnetic spectrum, are capable of oxidizing ammonia, at least to the nitrite form, radiations of a variety of wavelengths might be expected to be capable of producing free radicals and subsequent oxidation of ammonia. The importance of nonbiological oxidation of ammonia in soil is not completely known. It is believed by many workers to be insignificant compared with the biological processes (Waksman, 1952), and many experiments have failed to show appreciable nonbiological oxidation. Notwithstanding, it is possible that such reactions may occur in soils, though perhaps to a small degree, under the influence of such radiations as sunlight, cosmic rays, and natural radioactivity.

V. Factors Affecting Sorption and Loss in the Soil

Clay minerals, soil organic matter, and soil moisture take part in the sorption of ammonia by soil. Soils may vary in the amount and nature of ammonia sorption depending on the status of the soil with respect to these variables. Chemical or irreversible sorption would depend on the amount and kind of clay mineral as well as its pH or ability to supply H^+ ions. It would also be dependent on the amount and nature of the organic matter. Physical sorption, or reversible sorption, would be dependent upon the amount of colloidal material in the soil, inorganic and organic, and would serve as a temporary repository of ammonia until it either underwent chemical reaction or volatilized into the air upon reduction of the partial pressure of ammonia. The soil moisture might also be pictured as a temporary solvent for ammonia from which it either reacts chemically with the soil or is lost by volatilization to the atmosphere. This suggests that in the fertilizer application of materials containing free ammonia, loss might occur once the chemically reactive sites in the soil are satisfied. Volatilization losses will also occur when soil conditions are favorable for the production of ammonia from organic matter or ammonium salts and the ability of the soil to react chemically with the ammonia is low.

A. Soil Moisture

Soil moisture might be expected to be influential in the sorption of ammonia in soils. Ammonia will of course dissolve in water, the amount depending on the partial pressure of ammonia. Upon reduction of the pressure, the ammonia may be volatilized into the air. Any ammonia that

does dissolve in the soil water is in a transitory condition since it either will react chemically with organic matter, or soil minerals, or will volatilize into the air if the partial pressure of ammonia is reduced. An exception to this might be in the case of soil moisture containing free acids, in which case the ammonia will react to form a salt and so be retained.

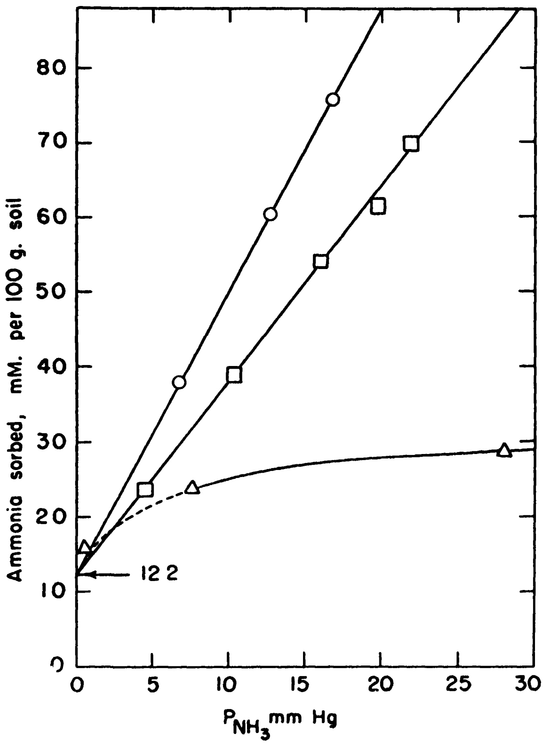

FIG. 1. Ammonia sorption by dry and moist Mardin silt loam at 25°C. (Peech unpublished). KEY: ○ = Saturation percentage, 50%; □ = Moisture equivalent, 32.1%; △ = Dried at 52% relative humidity.

Figure 1 taken from the work of Peech (personal communication) shows the effect of soil moisture content on sorption of ammonia. It is clear from these data that soil moisture sorbs ammonia and that the amount is linearly related to the partial pressure of ammonia once the chemical sorption capacity of the soil has been satisfied. Peech found from comparing the slopes of his sorption isotherms with the theoretical that the solubility of ammonia in soil water was the same as that in distilled water.

Stanley and Smith (1956) observed that ammonia loss from anhydrous ammonia application when plotted versus soil moisture content, passed through a minimum, being greater at the very wet condition and at the very dry extreme. Retention was highest at an intermediate moisture condition. They explained that losses from the wet soils were the result of the upward movement and evaporation of water containing dissolved ammonia, whereas from dry soils the losses of ammonia result from gas flow out of the soil as a result of pressure.

Jackson and Chang (1947) reported that moisture content over the range from air dry to field moist soil * exerts only a slight effect on sorption efficiency, and that this factor can probably be neglected in field practice. They suggest that since the soil has a tremendous capacity to sorb ammonia, loss of ammonia from the soil is not an important factor in the use of ammonia as a fertilizer.

B. Texture

Jackson and Chang (1947) investigated the effect of texture on the sorption of anhydrous ammonia by soils. Their results with respect to texture showed that Plainfield sand retained ammonia as efficiently as Crosby silt loam. Even in an air dry condition the sand contained enough clay (6 per cent) to provide adequate sorption capacity for ammonia. Jenny *et al.* (1945) however found ammonia uptake to be a function of soil texture. The sandy soils studied by Blue and Eno (1954) were found to allow appreciable ammonia loss upon application of anhydrous ammonia in the laboratory. Stanley and Smith (1956) also observed that loss of ammonia in the laboratory from sand was greater than from finer textured materials such as silt loam and clay. Martin and Chapman (1951) point out that the exchange or buffer capacity of a soil is important in determining nitrogen losses from NH_4OH or materials yielding ammonia upon decomposition. Soil texture must, of course, influence the total capacity to sorb ammonia. The amount of clay necessary to prevent losses in fertilizer application of anhydrous ammonia or aqueous solutions of ammonia cannot be fixed since retention would also be dependent upon a number of other factors such as kind of clay, pH, moisture content, organic matter content, depth of application, and amount applied.

C. Reaction

The acidity of a soil should affect to some extent the amount of chemically sorbed ammonia since a supply of hydrogen ions is necessary for the conversion of ammonia to the NH_4^+ ion. Jenny *et al.* (1945) found that acid soils tend to sorb more nitrogen from NH_4OH than from $(NH_4)_2SO_4$, while alkaline soils sorb more nitrogen from $(NH_4)_2SO_4$ than from

* "Approximately field capacity."

NH_4OH. They also found that sorption of nitrogen from $(NH_4)_2SO_4$ and NH_4Cl was governed by base-exchange reactions, and that exchange with these materials was equivalent. Sorption from NH_4OH however was found greatly to exceed the number of bases liberated. They reasoned that the ammonia may react with hydroxyl ions of the clay lattice.

Jackson and Chang (1947) studying sorption of anhydrous ammonia by soils found that alkalinity as provided by free $CaCO_3$ or Na_2CO_3 did not prevent satisfactory conservation of ammonia by a field moist soil when placement at rates up to 600 lb. of nitrogen per acre was at a depth of 2 to 4 inches. Humbert and Ayres (1957) working with aqueous solutions of ammonia on Hawaiian soils found that when the material was applied directly to the surface of acid soils, losses up to 15 per cent were obtained. When applied to alkaline soils, however, losses exceeded 50 per cent even when the ammonia was placed at depths of 4 inches, where the sorption capacity of the soil was exceeded. Martin and Chapman (1951) also observed considerable loss of ammonia when the pH of the soil exceeded 7.0. They also found more volatilization losses of ammonia when the exchangeable cation was sodium or potassium than when it was calcium or magnesium. They attributed this to the higher pH of the sodium and potassium saturated soil. Willis and Sturgis (1944) noted that a decrease in the H^+ ion concentration of soils resulted in greater loss of ammonia produced by microorganisms from soil organic matter. Steenbjerg (1944) found the pH value of soil was of decisive importance in loss of ammonia from $(NH_4)_2SO_4$. Ammonia loss was extraordinarily high when the soil contained free $CaCO_3$, but if the placement was at 6 cm. there was no loss regardless of pH and $CaCO_3$ content.

D. Organic Matter

Organic matter is important in the sorption of ammonia by soils. In sandy soils where the clay content is low it may be of special importance in the retention of ammonia. Some idea of the effect of removal of organic matter upon the sorption of ammonia by soils may be observed in data obtained by the author in Fig. 2. The ammonia sorption capacity of these two soils was reduced approximately by half when the organic matter was oxidized with hydrogen peroxide. The work of Sohn and Peech (1957) also shows the importance of organic matter in ammonia retention. They found that destruction of organic matter with hydrogen peroxide reduced the capacity of the soil to "fix" ammonia in nonexchangeable forms. They concluded from data on the decrease in ammonia retention after treatment of soils with hydrogen peroxide that at least 50 per cent of the ammonia fixed by New York mineral surface soils was the result of reaction of ammonia with soil organic matter.

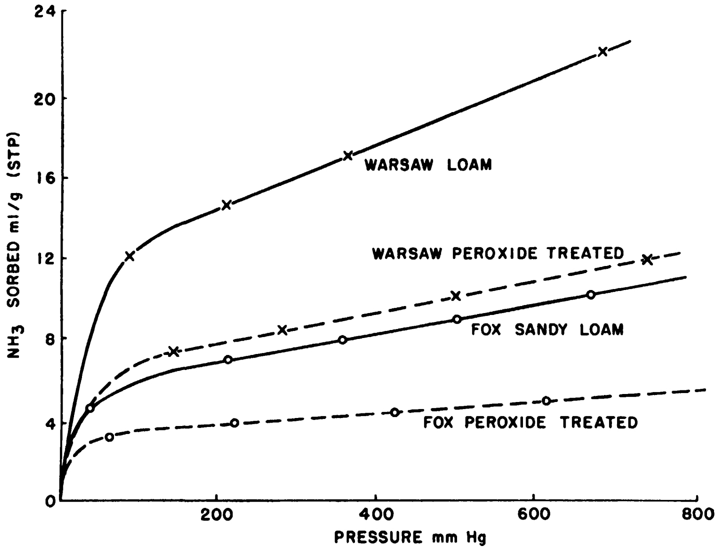

FIG. 2. Effect of oxidation of organic matter with H_2O_2 on ammonia sorption by two Michigan soils.

E. PLACEMENT

The effects reported in the literature of placement on sorption of ammonia by the soil from anhydrous ammonia and aqueous solutions of ammonia are quite variable. Jackson and Chang (1947) report that when anhydrous ammonia was applied at a depth of 1 to 2 inches in a soil of intermediate texture, moisture content, and pH, at the rate of 60 lb. of nitrogen per acre, there was little loss by gaseous diffusion. Satisfactory conservation of ammonia applied at the rate of 600 lb. of nitrogen per acre was obtained with placement at 2 to 4 inches. Stanley and Smith (1956) however observed appreciable loss from anhydrous ammonia when applied to sandy soils in the laboratory. Loss decreased with depth of application but was still high (10 per cent) in sand when application was at a depth of 9 inches. Peech (personal communication) concluded from his field studies of anhydrous ammonia application that losses of ammonia are negligible when the soil is at optimum moisture content and practical rates are applied at depths of 4 or 5 inches below the surface. Work reported by Hansen *et al.* (1957b) also showed that loss of ammonia from anhydrous ammonia was negligible with application at a depth of 4 inches in a sandy loam soil at a rate of 100 lb. of nitrogen per acre. These

measurements were made in the field over a soil moisture range of 7 to 16 per cent. The latter figure is approximately field capacity.

Studies on the effect of placement of ammonia solutions on ammonia loss have also been reported. Trickey and Smith (1955) found large quantities of ammonia were lost from ammonia solutions when applied on the surface of a silt loam soil. Hansen *et al.* (1957a) found appreciable losses of ammonia in the field with surface applications of solutions containing free ammonia. Placement 2 inches below the surface reduced losses to a low level. Humbert and Ayres (1957) reported a significant loss from volatilization when ammoniated irrigation water flowed from the head to the tail of 200-foot furrows. In some laboratory studies they reported losses from surface application of aqueous solutions of ammonia depending to a great extent on the reaction of the soil.

F. Tilth

Effects of soil structure on sorption of ammonia have not been widely investigated. Jackson and Chang (1947) reported that coarse tilth did not greatly interfere with efficiency of ammonia sorption from anhydrous ammonia. Stanley and Smith (1956) observed in the laboratory that ammonia movement and retention were greater in cloddy soil than where there was good crumb structure. They attributed this to the possibility that the ammonia could diffuse more rapidly through the larger pores of the cloddy soil and could more rapidly contact active soil surfaces, resulting in more efficient sorption.

The conflicting nature of the data on losses of ammonia from soils is evident in the preceding discussion. In the opinion of the author, this does not necessarily represent inconsistency but arises from the multitude of variables affecting ammonia sorption. Variations in techniques of measuring ammonia loss and laboratory versus field measurements also contribute to the variety of results reported. The influence of organic matter on ammonia retention especially has not received the attention it merits. From the work published, it is evident that large quantities of ammonia can be chemically fixed by organic soils and by the organic fraction of mineral soils. Whether complete or incomplete sorption of ammonia is observed in a sandy soil may be directly related to the amount and nature of the organic matter. In alkaline soils where there is a relatively small supply of hydrogen ions to react with ammonia, organic matter may be very important in the irreversible sorption of ammonia.

Since ammonia is sorbed chemically by clay minerals when enough H^+ ions are present (on the acid side) and it is sorbed chemically by organic matter to greatest advantage in the alkaline range, these two materials together provide sites for chemical sorption over a wide range in soil

reaction. Their combined action is probably very important in the conservation of ammonia by soils. It is likely, however, that ammonia chemically sorbed by these two soil constituents may be quite different in its availability for use by microorganisms or by higher plants.

In the final analysis, whether there is complete conservation of ammonia in the soil or not is dependent on two main factors: first, the total capacity or ability of the soil to react chemically with ammonia; second, the physical availability of the chemically active sites in the soil to contact ammonia in solution or in the gaseous state.

VI. Effects of Ammonia on Soil Properties and Organisms

Ammonia applied as a fertilizer in aqueous solutions or as anhydrous ammonia may affect the physical and chemical properties of soil and influence the organisms living in the soil.

A. Reaction

The immediate effect of an injection of anhydrous ammonia or application of an aqueous solution of ammonia, is to create a very alkaline reaction in the vicinity of the application. Subsequent biological oxidation of the ammonia to nitrate would be expected to modify this and tend to lower the pH. Stanley and Smith (1956) found that anhydrous ammonia increased the pH of Putnam silt loam soil to a distance of 4 inches from the point of ammonia release when measured 2 months after application. The original pH of the soil was 6.0, and was 8.1 at the point of injection, decreasing to 6.2 at a distance of 3 to 4 inches. Humbert and Ayres (1957) found that aqua ammonia injected at two rates, 500 and 1500 p.p.m., raised the pH of a Hawaiian Hydrol Humic Latosol from 5.0 to 6.2 and 7.1, respectively. The same treatments on a Low Humic Latosol raised the pH from 4.9 to 6.5 and 8.0; on a Gray Hydromorphic soil, from 7.3 to 8.8 and 9.5; and on a sandy Regosol, from 8.1 to 10.1 and 10.6. As nitrification proceeded, the pH of the band eventually dropped below that of the checks. The ultimate effect of ammonia on the reaction of a soil is to increase the acidity through the nitrification process. The immediate effect however is to increase the alkalinity.

B. Plant Nutrient Availability

Insofar as soil reaction affects the solubility and availability of various plant nutrients, applications of ammonia to the soil should affect the status of these materials. Another effect of ammonia might be expected to be that which results from cation exchange reactions where ammonium ions formed by reaction of ammonia and H^+ ions would come into equilibrium

with and influence the activity of cations on the exchange complex of the soil. Such changes in activity might be expected to affect the availability of these cations for uptake by plant roots. Ammonium hydroxide has a strong solvent action, as well as a hydrolytic action, on organic matter. Thus, applications of anhydrous ammonia or aqueous solutions of ammonia which result in localized regions of high concentration in the soil might be expected to result in solubilization and hydrolysis of certain fractions of the soil organic matter. The availability to microorganisms of these mobilized fractions presumably would be enhanced, as would the net mineralization of organic forms of nitrogen and phosphorus. Peech (personal communication) found large increases in inorganic and organic phosphorus as well as in the concentration of the ammonium ion in the soil solution as a result of anhydrous ammonia application. Organic matter dissolved in the soil solution increased markedly as a result of the ammonia treatment.

Stanley and Smith (1956) reported that applications of anhydrous ammonia decreased the amount of calcium that could be extracted from a Putnam soil with 0.005 *N* HCl. Measurements were made two months after applications. They also found that the application had relatively little effect on the extraction of potassium. The amount of available phosphorus was found to increase markedly. Anderson (1955) found that ammonia reduced the solubility of calcium and magnesium and increased the solubility of sodium, potassium, and phosphorus. These results were found prior to nitrification. The effects of ammonia on plant nutrients in soils could be expected to be quite variable and transitory. The chemical forms in which the nutrients exist, and the nitrification rate of the applied ammonia would be important factors. The solubility of mineral forms of phosphorus in the soil would be affected by the change in pH upon ammonia application. It is also possible that the ammonia would react with phosphorus compounds to form some of the more soluble ammonium phosphate compounds.

C. Soil Structure

Some published information indicates that ammonia may have an effect on soil structure. Smith (1954) has suggested that anhydrous ammonia is a "soil conditioner" in its effects on the physical properties of soil. His contention is that organic compounds are dissolved in aqueous solutions of ammonia, then coat the soil aggregates which become water-stable upon drying. Other results indicate the formation of a poorer soil structure. That NH_4OH has dispersive effects on colloids under certain conditions is well known. Jenny *et al.* (1945), studying the effects of NH_4OH on the percolation rate of water through soils, found that in five soils it improved

percolation rate compared with distilled water. In three there was no effect, and in four it lowered the percolation rate. How NH_4OH affects soil is likely to depend on the soil reaction. It tends to coagulate soils having neutral or alkaline reaction, whereas it tends to disperse or deflocculate acid soils. The fact that the ammonium ion may undergo fixation reactions with swelling 2 : 1 type clay minerals, in a manner similar to potassium, may also affect the physical properties. When these clay minerals have undergone fixation reactions with potassium or ammonium ions, they tend to lose their swelling characteristics. Such changes in properties of constituent minerals alter the physical properties of the soil. Anderson (1955) showed that ammonia treatment of a sandy loam soil decreased the percolation rate, whereas subsequent drying of the treated soil increased water-stable aggregates.

The actual importance of the improvement or debilitation of soil structure by ammonia applications has not been fully evaluated.

D. Plant Growth

The net effect of fertilizer applications of ammonia is to add to soil sources of nitrogen. This may greatly increase crop yields if other soil sources are limiting.

Ammonia, however, may be toxic to living organisms. It may exert a toxic or even lethal effect on the cells since at high concentration ammonia is a cell poison. In the application of anhydrous ammonia to soils, the tops of plants are affected whenever the free gas contacts them. Some effect on the roots when crops are side-dressed may also be expected. The extent of injury may be quite variable. Humbert and Ayres (1957), studying the effects of ammonia on the roots of sugar cane, observed discoloration of the primary root 6 days after treatment with 1500 p.p.m. of banded aqua ammonia. The root, however, grew normally and extended 20 cm. in the 6 days. Despite the discoloration of the roots, intensive secondary root development occurred in the treated zone. They concluded that side-dressing of sugar cane was a desirable treatment. Side-dressing with anhydrous ammonia is practiced on many crops apparently without producing undue toxicity.

E. Soil Organisms

Since ammonia is toxic to cells at high concentrations, it might be expected to affect the soil microbial population. Humbert and Ayres (1957) observed that aqueous solutions of ammonia injected in bands drastically reduced the numbers of nitrifying organisms in the bands. They thought of this as beneficial since it minimized losses by leaching of nitrate nitrogen

and resulted in effective utilization of the applied nitrogen. Eno *et al.* (1955) also observed reduction in nitrification upon anhydrous ammonia application at the rate of 300 p.p.m. They suggested that in the field the nitrification would be reduced in the zone of retention but not at the periphery. Therefore the nitrifiers would gradually reduce the concentration of ammonia centripetally until it was all utilized. Eno and Blue (1957) found that at certain concentrations of anhydrous ammonia, the oxidation to nitrate was stimulated much more than when equivalent amounts of ammonium sulfate were used. However, Boullanger and Massol (1905) found that free ammonia inhibited the growth of nitrite oxidizing bacteria. Aleem *et al.* (1957) investigating the accumulation of nitrites in soils of neutral to alkaline reaction also found that ammonia was a selective inhibitor of *Nitrobacter agile* and only slightly inhibited *Nitrosomonas europaea* even at high concentrations. Inhibition of the nitrite oxidizing organisms in pure culture increased with pH in the alkaline range, which indicated that ammonia rather than the ammonium ion was specifically toxic.

Eno and Blue (1954) found that anhydrous ammonia applications to Aredondo loamy fine sand and Lakeland fine sand decreased the number of soil fungi. Both bacteria and fungi were decreased the first day. By the tenth day fungi were still reduced in number while bacteria had increased and were 6 to 25 times as numerous as in the check. The drastic reduction in numbers of fungi suggested the possible use of anhydrous ammonia as a fungicide. Eno *et al.* (1955) found that, in addition to the reduction in numbers of fungi with anhydrous ammonia application, nematodes were affected. Compared to untreated soil only 0.6 per cent of the nematodes and 4.9 per cent of the fungi survived when 608 p.p.m. of nitrogen were present as ammonia. They observed that plant parasitic nematodes were greatly decreased and in certain cases some species could not be detected during counting. They suggested that the addition of anhydrous ammonia to soil may be of value in the destruction of plant parasitic nematodes in addition to its fertility benefits.

VII. Summary

The fate of an ammonia molecule in the soil may be summed up as follows: It may be immediately chemically sorbed by the clay minerals or organic matter. It may be physically sorbed by the colloidal complex or dissolved in the soil moisture. From these temporary repositories it may be eventually chemically sorbed or in the absence of available chemically reactive sites, may eventually diffuse through the soil pores to the surface

and be lost to the atmosphere. The ability of a soil to react chemically with ammonia is most certainly related to its clay and organic matter contents.

It has been suggested that ammonia is chemically sorbed in greatest quantities by clay minerals under acid conditions, i.e., when there is a supply of H^+ ions to react with the ammonia. Other work has shown that ammonia is chemically sorbed in greatest quantities by organic matter under alkaline conditions. In all likelihood, the combination of these two soil constituents will provide for chemical sorption of ammonia over a wide range in soil reaction.

The nature of the compounds formed upon reaction of ammonia with soil organic matter is an area of research which should be productive in the future. This is, of course, intimately tied in with research on the molecular structure of the components of soil organic matter and will probably advance as our knowledge of that subject increases. Information regarding the factors which affect the utilization of ammonia chemically fixed by organic matter is needed to evaluate fully the availability of such reacted ammonia to plants.

The effects of ammonia on soil organisms and on soil physical and chemical properties are still in need of study. Work on whole soil needs to be done, but it must be carefully interpreted. Soils of widely different properties are affected quite differently by ammonia application. In view of the large quantities of ammonia being applied as fertilizer and the unanswered problems with respect to its reactions with soil, it remains a fruitful area of research for the future.

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NEW GRASSES AND LEGUMES FOR SOIL AND WATER CONSERVATION

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Page

I. Introduction

A. Grass in the Conservation Program

In 1950 Wheeler stated that "the programs developed under the Soil Conservation Service have more directly encouraged the planting of soil-conserving grasses and legumes and the improvement of pasture and meadows than perhaps any other factor in recent years." Early studies reviewed by Bennett (1939) showed that the widespread occurrence of soil erosion was caused by cropping land not suited to cultivation, excessive use of row crops, incorrect tillage methods, and overgrazing of grasslands. He also reviewed studies showing that meadows, pastures, cover crops, and grassed waterways prevented erosion and runoff when properly managed. Other workers found that grasses and legumes, singly or together, effectively reduced erosion and runoff when combined with grain, fiber, vegetable, and other cultivated crops in well-designed rotations. Stripcropping and terracing were found to increase the effectiveness of rotations on some lands. These findings were reviewed by Browning (1951), Lamb (1952), Harper (1951), and Blakely *et al.* (1957).

Luker (1947) and Christ (1947) described the problems of soil deterioration on irrigated lands. Among the more important are erosion, waterlogging, leaching, and increase in salinity and alkalinity. Grass and legume crops are important in designing conservation practices to prevent or correct these conditions.

The relationship between the condition of the native vegetation on rangeland and erosion was studied by Forsling (1931), Renner (1936), and Craddock and Pearse (1938). Sampson (1952) reviewed this work which showed that as the plant cover was progressively reduced in kind and amount from that which was climax for the site, there was a disproportionate increase in erosion and runoff.

Grass, therefore, soon assumed a prominent place in conservation work.

The use of grasses and legumes in American agriculture was not new, but the conservation objective of using land within its capabilities and treating each acre according to its needs for protection and improvement created new uses for grass crops. Large areas of land would need to be converted from cash crops to grass, and grass crops were needed for stripcropping, soil-conserving crop rotations, cover cropping, gully and waterway control, stabilization of critical erosion areas, reseeding of depleted rangelands, and watershed protection. Along with the realization of these needs came an increased recognition for improvement in the culture and management of grass to assure its conservation effectiveness.

B. Developing Grasses and Legumes for Conservation

1. Species and Varieties

It was soon found that grasses and legumes needed for land conversion and treatment were not available in kind or amount to meet conservation objectives. The need was met by establishing Soil Conservation Service nurseries, as described by H. H. Bennett (1951).[1] The functions of these centers were threefold: to assemble and study grasses and legumes (and other plants) for specific use in conservation work, to determine the best culture and management for their use, and to expedite their production on farms and ranches. This work was done in cooperation with agricultural experiment stations and other state, federal, and private research agencies. The system devised to screen and develop materials and get them into production rapidly was described by Schwendiman and Hafenrichter (1955).

New grasses and legumes were obtained from three sources. Many of them were supplied by the Plant Introduction Section of the Agricultural Research Service and state experiment stations; several were domesticated from ecotypes in the native vegetation and from adventive stands; and large-scale seed harvests were made directly from native stands.

New species and varieties from foreign introduction or from adventive stands were increased on farms for use in all parts of the country. Native grasses were either harvested from natural stands or domesticated from this source in the Great Plains and the western states. H. H. Bennett (1951) stated that as a result of these activities more than 425,000,000 lb. of seed were harvested in 1950 in or through the activities of soil conservation districts.

Developing grasses and legumes for conservation work is often complex because these plants have multiple uses. They protect the soil surface from erosion, reduce runoff, and are used as forage in most cases. An even

[1] These nurseries were designated as Plant Materials Centers in 1956.

more important result from their use is the improvement of soil structure and fertility. Hence, there often is a complex plant-soil-animal relationship. Husbandry of the plant and the animal and a precise knowledge of soil conditions are required to obtain desired results (Hafenrichter, 1948).

Husbandry of the plant requires exact information concerning its adaptation to climatic factors which may vary rapidly over relatively short distances and fluctuate widely in different years in some parts of the country, notably in the Great Plains and the Western region (Bailey, 1941; Hafenrichter, 1948, 1952; Norum *et al.*, 1957; Hobbs, 1957; and Johnston, 1957). The conditions of low fertility and poor structure commonly encountered on large areas of eroded soils on agricultural land and on rangelands in poor condition often impose stringent limitations on the development of grasses and legumes. Many cultural methods are not applicable to use in conservation work. The system for mapping kinds of soil, including slope and erosion condition along with other environmental factors (all interpreted in terms of land capability classes, subclasses, and units) has aided materially in this developmental work. This system was described by Hockensmith (1948, 1952). For rangelands, an important guide is the mapping of range condition as was described by Dyksterhuis (1949). The system of developing grasses and legumes described by Schwendiman and Hafenrichter (1955) provided for sampling the major climatic and edaphic variations on farm and range lands.

The development of varieties and the use of ecotypes has progressed rapidly in the last twenty years. It has resulted from the cooperative work among investigators in several research agencies and between them and workers in action agencies. The extensive use of grasses and legumes in conservation work where conditions of soil and climate and use and management on farms and ranches are known, has emphasized the value of varieties with superior qualitative characteristics. There are now several examples where a new variety of a grass made possible the use of a good legume, or where a new variety of a legume implemented the use of a good soil-conserving grass. Advances also have been made in the development of varieties that have superior qualities for use on lands with pronounced limitations.

2. *Cultural Methods*

Many advances in the culture of grasses and legumes have been made. Most of these plants have small seeds, several are planted vegetatively, and mixtures of grasses and legumes are preferred in humid and irrigated areas. Willard (1951) presented a summary of the factors influencing establishment of forage crops on agricultural land in humid areas. He listed 19 possible hazards that might account for failure to obtain good stands.

He stated that most of them could be avoided by choosing adapted species and varieties, preparing good seedbeds, seeding at the right time and depth, providing plant nutrients, and protecting seed and seedlings from diseases and insects. Erdman (1957) showed that strains of legume bacteria differ in their ability to fix nitrogen and to improve the growth, yield, and quality of legumes and that this difference might be a factor in establishment and production.

Wagner (1956) reviewed the literature and reported the results of experiments with band seeding to establish pastures under humid temperate conditions. The reasons for superiority of band seeding in early establishment and growth were given as: (1) readily available fertilizer is easily accessible to seedling plants, (2) less of the fertilizer is taken up by competing weeds, and (3) there is less reversion of nutrients into relatively unavailable forms because contact of the fertilizer with the soil is restricted. This method has special application to low fertility soils.

Chapin *et al.* (1951) called attention to the advantages of planting grasses and legumes in alternate drill rows to eliminate competition between these two kinds of plants during the seedling stage. Competition during this stage may result in dominance of the grass if the seeding is made in cool, wet weather and dominance of the legume if warm, dry conditions obtain. Woods *et al.* (1953) used the alternate-row method to study the compatibility of a large number of grass-alfalfa mixtures on eroded soil. Uniform composition was consistently obtained by using this method, and competition was reduced in subsequent years. McWilliams (1954) reported similar results. Stark *et al.* (1946) successfully used this method to establish mixtures of drought-tolerant grasses under semiarid conditions. This method has been used extensively in the field with good results by MacLauchlan (1957).

Cultural methods that proved successful for reseeding with grass on depleted rangelands in the Western region are described by Short and Woolfolk (1952), Miller *et al.* (1953), Allred and Nixon (1955), Lavin and Springfield (1955), Hull and Johnson (1955), Cornelius and Talbot (1955), Rummel and Holscher (1955), Plummer *et al.* (1955), and Anderson *et al.* (1957). The salient features of this work are removal of competition from weedy grasses, forbs, and shrubs that are found on such land, proper covering of the seed, and protection of the young seedlings until they are completely established.

Stark *et al.* (1946) conducted a series of intensive trials on eroded soils in a 9-inch rainfall zone that once were cropped to dryland grain but which were later abandoned. They compared several methods of seedbed preparation and dates and methods of seeding, and planted several drought-resistant grasses and mixtures. The more intensive methods of

seedbed preparation were best and most economical. They effectively reduced competition from volunteering annual grasses, weeds, and shrubs. Seedings on well-prepared seedbeds came into full production and were ready to graze at least one year sooner than those on poorly prepared land. Intensive methods of land preparation made it possible to seed both in the fall and spring and to use a wider variety of seeding machinery. These methods also reduced the hazards of climatic variation among years. This last factor causes many failures in low rainfall areas, especially on eroded soils.

Many new grasses that were otherwise promising in conservation work on farm and rangelands were difficult to seed accurately, either alone or in mixtures, because of small seed size, awns, fluffy appendages, or burs. Three methods were devised to overcome these difficulties.

Weber (1939) and Schwendiman *et al.* (1940) devised methods for processing seeds with awns or appendages. A modified hammer mill adjusted in cylinder speed and screen size was used to remove undesirable appendages. After regular cleaning, the seeds were easy to plant with drills.

A dilution method to facilitate planting was described by Lemmon and Hafenrichter (1947). They used cracked and screened barley to plant many different sizes and shapes of grass and legume seed with but a single setting of the drill. The method consisted of using a standard volume of cracked grain per acre from which an amount equal to that of the seed to be planted was removed. The seed was then mixed with the remaining diluent. Especially uniform stands were obtained, and, by placing dividers in the grain box of a drill, alternate-row seedings of two seeds widely different in size and shape were possible with the same drill setting. The method was improved by Hoglund and described by Southworth (1949). Unprocessed rice hulls were used as the diluent, and when adequate quantities of hulls were used no adjustment in the volume or weight of hulls was necessary except with exceptionally fluffy seeds or burs.

Specialized machinery was described by Collins (1952) and Stoesz (1952) for planting trashy seeds of native grasses that are used extensively in reseeding abandoned croplands and depleted ranges. Other seeding machinery especially adapted to use on newly cleared, rough, or stony land is described in the "Handbook—Range Seeding Equipment" (Anonymous, 1957b).

3. *Management Methods*

Management of grasses, legumes, or mixtures of the two is a dominant factor in determining the performance and effectiveness of these plants.

Good management methods are especially important in conservation work where soil, erosion, and other site conditions often impose limitations on stand, growth, yield, and survival. Osborn (1952) showed that density of stand and amount of growth were directly related to effectiveness of vegetation for control of runoff and erosion. Wheeler (1950) and Hughes *et al.* (1951) discussed the principal management methods for hay, pasture, and cover crops for the major crop zones of the United States and provided extensive bibliographies. Hafenrichter (1957) reviewed the literature and discussed management of grasses and legumes on seeded and native hay meadows, humid and irrigated pastures, and native and reseeded rangelands in the Western region. Special emphasis was placed on interactions between the factors of time, method, and intensity of grazing, and botanical composition, density of stand, and growth and production. All of these interactions are modified when fertilizers are used in humid and irrigated areas and when water is applied to irrigated meadows and pastures.

C. Regions and Areas

Many grasses and legumes are required for conservation work on farm and range land in a country as large and diverse in factors affecting plant growth as the United States. Therefore, the country will be divided into generalized regions which reflect the major factors of climate, soil, land use, and erosion which in turn influence the use, culture, and management of these plants in conservation work. Major divisons of the United States have been made by several authors, and others have subdivided them to reflect more precisely some factors that influence plant growth. Aamodt (1941) presented five major pasture regions, and Hein (1951) divided each of them into two parts to show the major climatic influences affecting the distribution of the principal species of grasses and legumes. Crawford and Hurd (1941), Tabor (1946), Hafenrichter *et al.* (1949), and Cooper (personal communication, 1957) made further subdivisions for parts of the country more precisely to express adaptation and use of these plants in conservation work. Barnes (1957) recently divided the country into 16 regions, primarily on the basis of soils and climate but also to express the principal land uses.

Four generalized regions will be used in this discussion. They will be designated as Northeastern, Southeastern, Great Plains, and Western. These regions were chosen primarily on the basis of major climatic differences and the influence they have on the choice of species. Each region will be divided into two or three areas which experience has shown influence the performance of varieties and ecotypes as well as species of grasses

and legumes in conservation work. Reference will be made to land capability classes, subclasses, or units that reflect factors which determine land use and the use, culture, and management of plants for conservation.

Nearly all of the grasses and legumes used in conservation work in the two eastern regions are exotic or adventive species. In contrast, native species are widely used in the two western regions, especially on land not suited for cultivated crops. However, many exotic grasses and legumes and some domesticated native grasses are used on cropland in these two regions.

II. The Northeastern Region

A. Description

The Northeastern region lies east of a line approximating the 98th meridian and north of a line approximating the southern boundary of Missouri, Kentucky, and Virginia. Conditions in this region are generally favorable for the growth of grasses and legumes. Total annual rainfall increases from west to east and from north to south, and much of it occurs during the growing season, April to September. The length of the growing season increases from north to south but is modified by topography

The Northeastern region can be divided approximately in the center between its boundaries to show the adaptation of grasses and legumes to climatic conditions. These two divisions will be designated as the northern and southern areas. A few species of grasses and legumes have wide adaptation, but the range of others was limited until new varieties were developed. Conditions of shallow soils, poor drainage, erosion, and low fertility limited the use of a number of species, but advances in plant culture have been made to overcome some of these restrictions.

Patrick (1947) pointed out the causes and extent of wind, water, and streambank erosion in the eastern half of this region. He cited the use of sloping land for intensive crop production as one of the major factors causing excessive runoff and erosion. Musser (1947) stated that the clean-tilled crop type of agriculture on sloping land was the greatest contributing cause of widespread erosion in the western half of the region. He also showed that land capability summaries indicated a need for converting land use, increasing the use of grasses and legumes in pasture and crop rotations, and supplementing these changes with contouring, stripcropping, diversions, and other structural measures.

The need for changes in land use and for soil and water conservation increased the use of grasses and legumes in this region and gave impetus to the introduction of new species and the development of better varieties.

Some native grasses were domesticated for use on land in low capability classes.

Kentucky bluegrass, timothy, orchardgrass, and redtop; white, red, and alsike clover; sweetclover; and some alfalfa were used in the region prior to the conservation movement; and they are still important species. As a result of introduction, development of varieties, and use according to land capability classes, bromegrass, tall fescue, birdsfoot trefoil, lespedeza, and new alfalfa varieties are used for erosion control, forage, and soil improvement. Several other grasses and some legumes have special-purpose uses in agriculture, and this list has also been augmented with species having primary value for erosion control.

Two kinds of plantings of grasses and grass-legume mixtures are used for soil and water conservation. Permanent seedings are made on lands in the lower capability classes that should not be cultivated or that must be plowed infrequently. Such land can be used for pasture or hay. Permanent plantings are also made on waterways, highway cuts and fills, dikes, gullies, and sand dunes for erosion control. Although important for soil and water conservation, the acreage of these plantings is not large, and some of them are harvested for forage. Livestock or cash crop farmers make extensive use of grasses and legumes in rotation for hay, pasture, and soil improvement on cropland in the better capability classes. They provide excellent control of runoff and erosion when well managed and are often supported with contouring, stripcropping, and terraces.

B. Grasses Widely Used

Orchardgrass (*Dactylis glomerata*) has been used more in the southern than in the northern area of the region. Fuelleman *et al.* (1949) indicated that orchardgrass did not stand severe winter cold, and Wheeler and Hill (1957) stated that it would stand more heat, drought, and lower soil fertility than bromegrass or timothy. However, the use of this grass for pasture seedings in the northern area is increasing, particularly since mixtures with the hardy alfalfas are used for pasture and improved pasture management practices are used. Although most of the seed that is planted is common orchardgrass, the use of S-37, BRAGE, and S-26 varieties is increasing in the northern areas (Briggs and Steiner, personal communications, 1957), and POTOMAC has recently been released for use in the southern area. The conservationist is interested in the production of fibrous roots by orchardgrass, and Woods *et al.* (1953) found that the yield of roots was high in alfalfa-grass mixtures.

Timothy (*Phleum pratense*) is still an important constituent of meadow and pasture seedings in the northern area. This grass grows on a wide range of soils but is best suited to clay loams and silt loams of average to

high fertility. It develops rapidly to produce a good ground cover and provides pasture before the slower developing species in the mixture reach full production. Evans (1946) and Fuelleman *et al.* (1949) gave preference to the later strain, LORRAINE, in the northern area and to the early strain, MARIETTA, in the southern area. These two varieties are described by Evans (1946) and Wheeler (1950). Jones (personal communication, 1957) and Steiner (personal communication, 1957) indicate that CLIMAX timothy is preferred in the eastern half of the northern area. A short description of this variety was given by Wheeler and Hill (1957).

Bromegrass (*Bromus inermis*) has only recently become important in most of this region. The recognition and development of varieties of the southern types had a great influence on the rapid spread of this grass in the Northeastern region. Another influence was the improved management of pastures that showed the advantage of the taller and leafier grasses and of grass-alfalfa mixtures. Mixtures of bromegrass with legumes, particularly alfalfa, have multiple use for hay, pasture, silage, and soil improvement. Bromegrass requires fertile, well-drained soils for good production. The varieties ACHENBACH, ELSBERRY, FISCHER, and LINCOLN are of the southern type and similar in yield, early spring growth, strong sod-forming habits, and drought tolerance. All of them have been superior to varieties of the northern type in this region. Comparisons were made by Newell and Keim (1943), Thomas and McPherron (1949), and Wilsie (1949). These varieties have been released and registered, and seed is grown under certification in one or several states. The varieties of the southern type of bromegrass were described by Hein (1955a), and a synoptic description of them and of other types was given by Wheeler and Hill (1957).

Tall fescue (*Festuca arundinacea*) is another grass that was not commonly used in the Northeastern region until its performance in conservation seeding was noted. Although it will grow on a wide variety of soils, it is especially adapted to lands in low capability classes because of poor internal drainage or inundation in the winter months. The dense rosette of basal leaves provides protection against erosion, and a high production of strong fibrous roots improves soil tilth. Tall fescue is winter hardy and remains green during the summer months in the presence of some soil moisture; hence, it can be used in both the northern and southern areas of the region. Mixtures of tall fescue with white, Ladino, or alsike clover are pastured. Tall fescue is used to stabilize waterways, terrace outlets, diversions, lanes, and road cuts and fills. Both KENTUCKY 31 and the ALTA varieties of tall fescue are used, and little difference in performance has been noted.

Kentucky bluegrass (*Poa pratensis*) and redtop (*Agrostis alba*) are not new to the agriculture of the region, but they have special uses in

conservation work. Both of these grasses are adapted to land where other grasses cannot be used. Kentucky bluegrass can be used for pasture on shallow soils or steep sites that must have a permanent cover. It is used to stabilize waterways, diversions, and other erosion-controlling structures. It must be limed for good production of cover and pasture when grown on acid soils. Fergus (1951) described factors influencing adaptation and yield of Kentucky bluegrass, especially soil fertility, soil pH, temperature, and precipitation. Redtop has long been known for its adaptation to eroded and low-fertility sites, poorly drained soils, acid soils, and a wide variety of climatic conditions. It is used in conservation work to provide erosion control on land in low capability classes. Redtop is still used in some pasture mixtures (Fuelleman *et al.*, 1949), but it is being replaced by other grasses (De France, 1951).

C. Grasses with Special Uses

Several grasses have special uses in soil and water conservation. Hawk *et al.* (1954) described three methods that were developed for using reed canarygrass (*Phalaris arundinacea*) to stabilize gullies, grass flumes, shaped waterways, diversion terraces, and the banks of farm ponds. Seedings were successful when firm, clod-free seedbeds could be prepared and good seed was used. Sprigging with small sod pieces assured good stands that quickly developed a good cover. The use of this grass for erosion control led to the establishment of "sod banks" in soil conservation districts. The IOREED variety of reed canarygrass was used for this purpose. The "green hay" method for establishing reed canarygrass was successful when good planting material was selected and the culms were carefully covered with soil. Moderate grazing or periodic mowing were beneficial to the use of reed canarygrass in water-controlling structures.

Switchgrass (*Panicum virgatum*) is native to the tall grass prairies in the western part of the region. It is a summer-growing, sod-forming grass that grows under moderately wet conditions but will also stand intermittent drought. It produces cover on soil with a low nitrogen level but will respond to improved fertility. Hawk (personal communication, 1957) has observed that it has promise in the western part of the region for use in shaped waterways that are intermittently wet and dry and are low in fertility. Switchgrass is used to stabilize sandy lands on the coastal plains in the eastern part of the region (Steiner, personal communication, 1957). Good hay and silage are made from switchgrass, and the BLACKWELL variety that is described by Wheeler and Hill (1957) is preferred. Fuelleman *et al.* (1949) pointed out that switchgrass has weak seedlings and is slow to become established. However, Hawk (personal communication, 1957) has successfully used Canada wildrye (*Elymus canadensis*) as a compan-

ion crop to make quick growth and suppress weeds until the switchgrass was established. This is a rapid-developing bunch-type grass from the native vegetation.

Some use is made of ILLAHEE red fescue (*Festuca rubra*) and Chewings fescue (*F. rubra commutata*) to stabilize soil on airports, road cuts and fills, and on other embankments. Red fescue produces a good erosion-resisting sod, but Chewings fescue is more tolerant of drought conditions. The strong rhizomatous and stoloniferous habit of Japanese lawngrass (*Zoysia japonica*) produces a tough sod. It is planted from sod "plugs" to control erosion on waterways, spillways, level-lip spreaders, and embankments that cannot be stabilized by seeding other grasses because of high water velocities. Its use is confined to the eastern part of the southern area of the region where warm humid conditions obtain. An especially vigorous clone, Z-73, is preferred for this work (Steiner, personal communication, 1957).

Still quite new but useful as a winter cover crop in orchards is SVALOF field brome (*Bromus arvensis*). This self-seeding, winter annual grass has a dense but short top growth that provides surface protection and is easily reduced to a mulch in the spring. Colby (1956) compared it with rye and showed that it produces twice the tonnage of fibrous roots for soil improvement. Care must be taken when reducing the cover in the spring so that enough plants remain for reseeding. Although careful management is necessary, field brome is promising for winter cover on land used to grow row crops such as vegetables, tobacco, corn, or soybeans.

American beachgrass (*Ammophila breviligulata*) is used to stabilize sand dunes. Stoesz and Brown (1957) pointed out that it is especially effective for coastal dunes and has promise for use on inland sands. The plantings are made vegetatively, and special provision for maintenance is required to insure stabilization. Weeping lovegrass (*Eragrostis curvula*) is used to stabilize highway cuts and fills, banks of drainage ditches, pond embankments, and sand blow areas in the eastern part of the region. Its special qualities for such work were described by Crider (1945). Among the more important attributes are adaptation to land in low capability classes, ease of establishment, good ground cover, an extensive and tenacious root system, and natural reseeding. No special strains have been developed, and the one in use bears the original Soil Conservation Service number A-67.

D. Legumes Widely Used

Legumes in widespread use in this region are alfalfa, sweetclover, and red, Ladino, white, and alsike clovers. All of these legumes have been used for forage and for soil improvement in the region, and their adaptation and

value are widely recognized. However, the development of new varieties of several of them has extended the areas where they are successfully grown. VERNAL alfalfa with its greater winter hardiness and equal wilt resistance extended the limits of use in the western part of the northern area beyond that of the RANGER variety. NARRAGANSETT and ATLANTIC are not wilt resistant but are winter hardy and have increased the use of alfalfa in the eastern part of the northern area.

KENLAND red clover was developed for its resistance to southern anthracnose and MIDLAND for its resistance to northern anthracnose. Steiner (personal communication, 1957) reported that PENNSCOTT red clover has good seedling vigor, good production, and hardiness in the eastern part of the northern area where it is used in hay mixtures. This variety was described by Hollowell (1953). It is similar in disease resistance to the KENLAND variety. PILGRIM white clover, which is very similar to Ladino clover but more winter hardy, has extended the use of this legume into the parts of the region where hardiness is an important quality.

Two new legumes, birdsfoot trefoil and lespedeza, are recent introductions to this region that are adapted to land in the lower capability classes and whose area of use has been extended by development of new varieties.

Broadleaf birdsfoot trefoil (*Lotus corniculatus*) is especially valuable in conservation work because it can be used on land in low capability classes due to shallow soil, low fertility, high acid reaction, or high water tables. Such lands are not adapted to the production of alfalfa or red, Ladino, and alsike clover. On them, as well as on steep lands requiring a good cover for erosion control, birdsfoot trefoil has been a useful legume for permanent pastures (G. F. Brown, 1950). The history of the early encouragement for the use of this legume in soil conservation work was given by McPherron (1954). MacDonald (1946) described the plant and appraised its value as a forage legume, and Hughes and MacDonald (1951) cite many references giving its cultural requirements.

Birdsfoot trefoil has many values as a permanent pasture legume. It grows on a wide variety of soils, produces good yields of forage and roots, and does not cause bloat. Although it persists on eroded soils and soils that are low in fertility, it responds markedly to phosphorus. This legume has been especially successful when seeded on renovated bluegrass pastures on land that requires permanent cover, provided the land was topdressed with phosphate fertilizer. The EMPIRE variety that was developed from an adventive stand in New York has consistently given better results under pasture conditions than imported European trefoil (Hughes and MacDonald, 1951; McPherron, 1954). Pierre and Jackobs (1953) presented results from clipping studies indicating that the method of grazing

may have an influence on the relative yield, root weight, and persistence of varieties.

Three species of lespedeza—striate (*Lespedeza striata*), Korean (*L. stipulacea*), and sericea (*L. cuneata*)—are especially adapted for use on land in low capability classes in the southern area. Striate and Korean lespedeza are annual and sericea is perennial. The fertility level requirement of these legumes is low, and they make good growth on acid soils. In mixtures with bunchgrasses they check erosion, gradually improve eroded and wornout land, and are used for hay and pasture. The annual species persist when they are managed to allow reseeding. The development of varieties of annual lespedeza has extended the area of adaptation of these legumes. COMMON and KOBE are varieties of striate lespedeza; COMMON is better adapted for use in permanent pastures and KOBE for hay. Korean lespedezas are adapted to the same soil conditions as striate, but they can be used further north. ROWAN is a variety of Korean resistant to nematodes. IOWA 6 is resistant to wilt and is early; hence, it can be used still further north. Sericea lespedeza is used with grass on road cuts and fills, borrow pits, and to stabilize other low capability sites. It can be used for hay or pasture but must be carefully managed to get proper utilization.

E. Legumes with Special Uses

Three legumes have special use in conservation work in the Northeastern region. Crownvetch (*Coronilla varia*) is a relatively new perennial legume that has shown promise for controlling erosion on dikes, highway embankments, gullies, and similar low capability sites in both the southern and northern areas of the region. Steiner (personal communication, 1957) reported that it tolerates a wide range of soils from moderately-drained clay loams to sandy and gravelly soils. It prefers soils with a pH of 6.5 or higher. A dense mat of surface vegetation is produced from fleshy rhizomes, and a large amount of fibrous roots is produced in the soil. This legume establishes slowly and grasses are sometimes planted with it to give surface protection the first year. Briggs (personal communication, 1957) stated that seed can be used to establish crownvetch on large areas, but on small areas living crowns are more practical. Some soil conservation districts have established crown "banks" to have a ready supply of propagating material. An improved variety, PENNGIFT, has been released. It was described by Grau and Grau (1952). Kudzu (*Pueraria thunbergiana*) is limited by temperature to the eastern part of the southern area and is used to stabilize deep gullies and high embankments. Hairy vetch (*Vicia villosa*) with cereal rye or wheat provides winter cover to protect the soils from erosion in orchards and on other land.

III. The Southeastern Region

A. Description

In 1947 T. S. Buie, in describing soil conservation and good land use in the Southeastern region, stated that there is a much larger area of severely eroded land in this region than in any other distinct region of the country. But he also stated that no region was advancing more rapidly from soil-depleting to soil-conserving types of crops. Grasses and legumes have played a major part in this land use conversion. Buie also stressed the need for water conservation in this region where the torrential type of rainfall is common. Here damaging floods occur, and deposition of sediment and erosional debris is costly.

For the purposes of this discussion the Southeastern region will include the area east of a line approximating the 98th meridian and south of a line approximating the northern boundaries of Arkansas, Tennessee, and Virginia. In broad terms the region can be divided into three areas: the Coastal Plains along the Atlantic Ocean south of South Carolina and along the Gulf of Mexico, including peninsular Florida; the Upland Cotton Belt; and the area north of the Cotton Belt. The conditions affecting land capabilities and adaptation and use of grasses and legumes in conservation work are soil depth, texture, fertility, and drainage; temperature and length of day; and degree of erosion as influenced by topography and land use. Tabor (1946, and personal communication, 1952) stressed crop climate and soil fertility level as determining factors in adaptation and showed that significant variations in these factors separated the three areas and also divided them into subareas.

The conservation movement was especially influential in increasing the acreage of grasses and legumes in the Southeastern region. Buie (1955) stated that hay, pasture, and other grass crops had increased from slightly more than 31 million to nearly 65 million acres in 25 years. New species were introduced, and new and better varieties of old species were developed. Some have multiple use for forage, prevention of erosion and runoff, and improvement of soil fertility and structure, while others have specific uses related to soil conservation. Improved management methods are being applied as the use of grasses and legumes increases. Two broad classes of grasses and legumes are used in the Southeast: warm-season and cool-season. Sometimes they are planted on the same field, but management is simplified if they are grown separately, especially when they are grazed.

B. Warm-Season Grasses

Bermudagrass (*Cynodon dactylon*) is adventive and is the most widely distributed pasture grass in the region. This warm-season, long-lived perennial grass is used for pasture, hay, meadow outlets, and for stabilizing road shoulders and detention structures. It will grow on most well-drained soils and persists even if the soils are eroded or low in fertility, but in the presence of adequate moisture it responds quickly when fertilized, especially with nitrogen. Burton (1951) has developed several hybrids, but the one called COASTAL has demonstrated marked heterosis and other superior qualities. Among these improvements are longer stems, leaves, and rhizomes; greater resistance to frost; more growth in the fall; and resistance to root-knot nematodes. These qualities improve the conservation usefulness as well as yield for forage. COASTAL Bermuda is planted from sprigs because the hybrid sets little seed.

Carpetgrass (*Axonopus affinis*) occurs on all lowland soils in the Coastal Plains area. It is adapted to low-fertility soils with acid reaction and is also found on this type of soil beyond the Coastal Plains area. Pure stands of this sod-forming, summer-growing grass occur when fertilizers are not used, and under these circumstances it often crowds out better grasses and legumes. It is not seeded but is scattered by grazing animals. With minimum fertilization it has a place when land capabilities common to poor, damp, sandy soils require semi-improved pasture. Burton (1951) does not recognize any varieties, but Wheeler and Hill (1957) mention a broadleaf and a giant variety.

Bahiagrass (*Paspalum notatum*) is another warm-season, sod-forming perennial grass especially well adapted to sandy soils and to soils of relatively low fertility in the Coastal Plains area and the lower half of the Upland Cotton Belt area. It is used in waterways; for stabilizing detention structures, roadbanks, and road shoulders; and for pasture. Bahia is not exacting as to soil requirements and maintains dense sods with moderate fertility. When a high level of fertility can be maintained, other tame grasses are preferred. Burton (1946) described six types of Bahia, and Tabor (1950) reported the collection of several naturalized types and introductions. Two of these types have become important: the common or broadleaf Bahia and the narrowleaf PENSACOLA variety. The latter is more frost and cold tolerant and has extended the area of adaptation northward. It is more vigorous and produces high yields of forage. Tabor (1957) traced the history of PENSACOLA Bahiagrass and states that more than 10 million lb. of seed have been produced in the last seventeen years. Seed is grown under certification in Georgia.

Dallisgrass (*Paspalum dilatatum*) will grow on a variety of soils throughout the Upland Cotton Belt and Coastal Plains areas but prefers heavy or loam soils. It is primarily a summer grass but has a long growing season. Because it is primarily a bunchgrass with very short rhizomes and many basal leaves, it is particularly adapted to pasture use with legumes, especially along the Gulf Coast. No improved varieties have been produced, but H. W. Bennett (1951) reported a selection that is superior in ease of establishment and production.

Among the warm-season species, Johnsongrass (*Sorghum halepense*) is best adapted to heavy clay soils of high fertility and waterholding capacity throughout the Cotton Belt area. H. W. Bennett (1951) pointed out that the usefulness of this grass for pasture and hay overshadowed any disadvantages it has as a possible weed. He also stated that good root production made it valuable for controlling soil erosion. No improved varieties are yet available.

Perennial warm-season grasses with restricted use in conservation work are ARGENTINE Bahia for pasture and water disposal systems in the Gulf Coast area; browntop millet (*Panicum ramosum*) for cover cropping, pasture, and hay in the eastern part of the Cotton Belt area; and Vaseygrass (*Paspalum urvillei*) for waterways and pasture on wet lands in the Upland Cotton Belt and Gulf Coast areas. Weeping lovegrass (*Eragrostis curvula*) has outstanding adaptation to exposed low-fertility level sites. It is used to stabilize road cuts and fills, borrow pits, gullies, and other similar sites. When adequate moisture is present the foliage remains green into the winter and can be grazed. Crider (1945) described its adaptation and use and showed that it produces a high tonnage of fibrous roots for soil conservation.

Subtropical in adaptation and used in peninsular Florida are the following pasture grasses: Pangolagrass (*Digitaria decumbens*) with rather wide adaptation to soils, Rhodesgrass (*Chloris gayana*) on well-drained fertile soils, caribgrass (*Eriochloa polystachya*) and paragrass (*Panicum purpurascens*) on wet lands, and St. Augustinegrass (*Stenotaphrum secundatum*) on soils with high organic content. Pangolagrass is also useful in waterway seedings.

Rescuegrass (*Bromus catharticus*) is strictly a winter annual grass with wide adaptation to humid areas with mild winters. It grows vigorously on good soils and matures an abundant seed crop in the spring or early summer. These characteristics make it ideal for a winter cover crop in orchards. It is also seeded with summer legumes for pasture in winter. The CHAPEL HILL strain is preferred in conservation work (Young, personal communication, 1957).

C. Cool-Season Grasses

Four cool-season grasses are used in seedings made for soil and water conservation. One of these has broad adaptation. Tall fescue (*Festuca arundinacea*) has spread rapidly in the northern area and the Cotton Belt area of the Southeast. No other grass has increased in acreage, as a result of conservation work, more than tall fescue. Bailey (1951) reported that more than one-half million acres had been planted during the fifteen-year period following the beginning of conservation work in the Southeastern region. Tall fescue is a cool-season grass that provides fall, winter, and spring grazing on a wide variety of soils. Bailey and Scott (1949) describe its uses in conservation work on lands in several capability classes. It makes a heavy sod that holds grazing animals, even on soils with restricted drainage. It is more tolerant of heat and drought than any of the cool-season grasses but does not grow actively under such conditions. The major conservation uses, aside from pasture, are erosion control on steep land, sod in terrace outlets and other water-disposal structures, and stabilization of detention structures. Root production is high and contributes to the improvement of soil structure when seedings are used in rotation with cash crops. KENTUCKY 31, a variety developed from an adventive stand found on the farm of W. M. Suiter, is commonly grown in the Southeast. H. H. Bennett (1951) described the methods used to implement the increase of this variety in soil conservation districts.

Orchardgrass, another cool-season species, is used in rotation pastures in the northern part of the Southeastern region on well-drained fertile soils with good moisture-holding capacity. The preference for strains is for those from the seed-producing areas in Virginia and Kentucky, but the recently released POTOMAC variety has recognized superior qualities. This variety was described by Hein (1955b).

Two other cool-season grasses have special uses in this region. Timothy is restricted to the higher elevations in the area north of the Cotton Belt where it occurs in pasture mixtures for erosion control, soil improvement, and forage. Italian, or domestic, ryegrass (*Lolium multiflorum*) is used with legumes to provide winter cover on cropland. It is sometimes pastured. Perennial ryegrass (*L. perenne*) behaves as an annual under conditions in the Southeastern region.

D. Warm-Season Legumes

The same influences that increased the use of grasses in the Southeastern region since 1935 also increased the use of legumes. Among these factors conversions in land use, control of erosion, and improvement of soil

structure and fertility played an important part. Improvement in varieties followed increased use.

The factors that determine land capability classes, subclasses, and units influence the adaptation and use of species and varieties, but cultural practices, especially the use of fertilizers, may affect some of these relationships. In pasture mixtures some legumes often decrease in density unless the pasture is properly grazed.

Kudzu (*Pueraria thunbergiana*) and sericea lespedeza (*Lespedeza cuneata*) are perennial summer-growing legumes. Kudzu is planted for erosion control in gullies and on steep banks. This leguminous vine makes a dense ground cover on a wide variety of soil types in the Southeast but prefers well-drained soils with good moisture-holding capacity. It is planted from rooted crowns or cuttings in widespaced rows, and the use of manure, superphosphate, and potash at planting time insures establishment and production. Kudzu can be pastured, but close grazing quickly decreases the stand. This legume is usually grown alone rather than in mixtures. Its use in conservation work was described by Bailey (1944).

Sericea lespedeza is an excellent soil-building legume, especially on badly depleted acid soils where other legumes are difficult to establish. It is widely adapted to climatic conditions, but Young (personal communication, 1957) stated that it is not adapted to the short day lengths in the Gulf Coast area. Outstanding characteristics of sericea lespedeza are a deep, branching root system and the dropping of large numbers of leaves that create a dense mulch. It is used in long rotations on class III land,[1] for stripcropping supplemented with terracing on class IV land, and for seedings on class VI land that requires permanent cover. It can be used for waterway protection and in field borders on sloping land. Although the leaves of this legume contain tannin, it can be pastured, but grazing must be carefully done to maintain good stands and production. Sometimes in reseeding, crimson clover and roughpea are planted with sericea lespedeza for winter pasture. Tall fescue and rescuegrass have been tried for the

[1] The land capability classification is an interpretive grouping of soils for agricultural purposes in which all soils are placed into eight broad capability classes. Soils having a large number of alternative uses are placed in class I and those with few are placed in class VIII, and considering all uses collectively the risks of soil damage or limitations in use become progressively greater from class I to class VIII. Within a capability class, all soils have limitations and management problems of about the same degree of magnitude. The eight capability classes can be further subdivided into smaller, more specific groupings called subclasses and units. Capability subclasses are used to show the kinds of problems and limitations, and capability units are used to show soils that need similar management, and that have the same general suitability for use.

same purpose. Such opposite season mixtures must be carefully managed to retain their conservation value and forage production. ARLINGTON sericea lespedeza is a selection that is more vigorous and higher yielding than common sericea.

Annual legumes are widely used in conservation work in the Southeastern region. Lespedeza is the principal summer-growing legume. Tabor (personal communication, 1952) stated that more acres are in annual lespedeza than any other soil-conserving crop. According to Wheeler and Hill (1957) the use of lespedeza has increased from a few thousand to more than half a million acres in the past twenty years. Annual lespedezas are used for pasture, hay, and cover crops. They are especially valuable for improving land that has been depleted of fertility. Striate lespedeza (*Lespedeza striata*) is used in the southern areas and Korean lespedeza (*L. stipulacea*) is used in the northern. The development of varieties has progressed rapidly. Date of maturity and resistance to diseases have been the primary objectives. The KOBE variety of striate lespedeza is larger, has broader leaves, and is preferred for hay over COMMON striate lespedeza, but it produces less seed. TENNESSEE 76 is similar in use and area of adaptation to KOBE. Korean lespedeza has extended the range of use of lespedeza northward, but it is susceptible to bacterial wilt and other diseases. CLIMAX and IOWA 6 are varieties of Korean that are early and resistant to wilt (Wilsie and Hughes, 1947). ROWAN is resistant to certain nematodes, and this makes it useful in the eastern part of the region.

Both striate and Korean lespedezas reseed themselves when pastures and meadows are properly managed. Tabor (personal communication, 1952) indicated that thin stands of tall fescue, orchardgrass, or domestic ryegrass are sometimes seeded with annual lespedeza when the mixture is used primarily for pasture in long rotations. These are opposite-season mixtures and must be carefully managed to retain their composition. Helm (1951) describes the use of annual lespedeza as a self-perpetuating catch crop with spring or fall grain. The legumes can then be plowed down for soil improvement, pastured, or cut for hay.

E. Cool-Season Legumes

The major perennial cool-season legumes for this region are white clover (*Trifolium repens*), Ladino clover (*T. repens latum*), and alfalfa (*Medicago sativa*). They are somewhat restricted in use. The Ladino clover is used in pasture, particularly on rich alluvial soils, but does not seed well. It is replaced with white clover, LOUISIANA GIANT white, LOUISIANA S-1, and other varieties. Despite the poor seeding habits, these varieties persist once they are established, even though they tend to behave as winter annuals. The newer strains are heavier seeders and can be used in

mixtures with Bermuda and Dallisgrass, as shown by Blaser and Killinger (1950). Alfalfa is adapted to the area north of the Cotton Belt on well-drained, deep, fertile soils. Toward the southern part of its range it may be relatively short lived. Varieties such as ATLANTIC and BUFFALO are preferred.

The principal winter annual legumes in widespread use are crimson clover (*Trifolium incarnatum*), hop clover (*T. procumbens*), hairy vetch (*Vicia villosa*), and rough or Caley pea (*Lathyrus hirsutus*). All of these clovers are used as cover crops or in pastures except hop clover, which is primarily a pasture plant.

According to data presented by Wheeler and Hill (1957) the acreage of crimson clover has increased rapidly since 1936, a marked increase occurring since 1942. Wide adaptation to well-drained soils, value as forage, and improvement of soil fertility are the attributes of this clover. The development of reseeding varieties with a high percentage of hard seed increased the use of crimson clover in conservation work because it could easily be fitted into both long and short rotations. Crimson clover can be sown with grain and row crops for cover cropping and soil improvement and with Bermuda, Dallis, Johnson, and some other grasses for pasture. It responds to phosphate and potash fertilizers. This clover is sometimes used with grass in waterways and on road shoulders. The reseeding varieties—DIXIE, AUBURN, AUTAUGA, and TALLADEGA—are sufficiently similar to make them equally useful in soil conservation work (Young, personal communication, 1957).

Hairy vetch and the more popular smooth form are used for cover cropping and pasture. This vetch is not exacting in soil or climatic requirements in the Southeastern region. The practice of cover cropping is not as general as it formerly was, but vetch is being used for winter grazing on cropland. Young (personal communication, 1957) reports the use of the smooth form mixed with Caley peas and seeded over summer pastures for winter grazing on land in low capability classes.

Roughpea or Caley pea is adapted to the Upland Cotton Belt area. It prefers heavier and more fertile soils than vetch but is promising on other soils when lime is used. The primary uses are for cover cropping and for mixtures in water disposal areas that are pastured. The stand of this annual legume is retained by self-seeding from hard seeds.

Hop clover occurs spontaneously throughout the region and is a component of seeded pasture mixtures. The values of this clover in pastures are high-quality feed, persistence, and good growth in late winter and early spring. These qualities are important in a region making major adjustments in land use.

F. Legumes with Special Uses

Many other legumes are adapted to certain land capability classes and conservation use in the region but are restricted in use. Most of them have value as cover crops and several can also be pastured. Red and alsike clover are used in pastures north of the Cotton Belt area. Blue lupine (*Lupinus angustifolius*) and yellow lupine (*L. luteus*) were used for cover cropping and soil improvement, but the acreage has decreased and diseases were a principal factor. Crotalarias, both *Crotalaria mucronata* and *C. spectabilis*, noted for their adaptation to sandy soils and immunity to root-knot nematodes, are used as cover crops for soil improvement and also to reduce the population of nematodes for other crops in the rotation that are susceptible to these organisms.

Hairy indigo (*Indigofera hirsuta*) makes a most desirable orchard cover crop in the Coastal Plains area, including peninsular Florida. It is unfortunate that there is a hesitancy to making wider use of this erosion-controlling and soil-improving legume for forage due to a poisonous property.

IV. The Great Plains Region

A. Description

The Great Plains region is a large area of land. It has been variously described and delineated (Bennett, 1939; Thornthwaite, 1941; Aamodt, 1941). In the present discussion this region will be regarded as the area between the Continental Divide and a line approximating the 98th meridian. The area of the region is slightly more than one-sixth of the total land area of the United States. Most of the region, excluding the mountainous belt along the western border, was originally a natural grassland. The land is prevailingly level to undulating except along the major drainages. It slopes gradually toward the west from elevations of 1,000 to 2,000 feet at the eastern boundary to about 3,500 to 6,000 feet above sea level in the west. These differences in elevation have a bearing on the adaptation of grasses and legumes.

1. Causes of Erosion

Bennett (1939) regarded climate as the major factor affecting land use in the Great Plains region. The average precipitation varies between 10 and 35 inches and tends to increase from north to south and from west to east, and a high percentage falls during the growing season, April to September. However, there are wide unpredictable variations in precipitation among years, and Thornthwaite (1941) characterized the region as

one suffering meteorological excesses. Drought periods are common, wide extremes of temperature occur, and average wind velocities are high. H. H. Bennett (1939) described the hazards of wind and water erosion and the need for water conservation. He also indicated the need for careful adjustments in land use and management to compensate for the vagaries of climate.

McClymonds (1947) described the causes of erosion in the northern half of the region and suggested the measures needed for control. The highly variable and erratic climate was the major cause of incorrect land use and management and contributed to the severity of wind erosion. Native rangelands and meadows occupy a large part of the area, and these lands were susceptible to deterioration and erosion when incorrectly grazed, especially during drought periods. Water conservation by structures and proper tillage methods and by restoring vegetation was needed. It was estimated that more than 11 million acres of abandoned farmlands and range in poor condition needed reseeding.

Merrill (1947) stated that the cause of widespread wind erosion was incorrect land use, with lack of measures for erosion control in the more arid portions of the southern half of the region. Improper use of rangelands caused decline in grass production and the invasion of brush. Where the land was cropped, one-crop farming and the cropping of steep land, especially with intertilled row crops, had resulted in severe soil losses. He called attention to the need for land use adjustments, crop rotations, and cover cropping on cultivated lands supplemented with properly designed structures to control runoff water from torrential rains. Rangelands in poor condition would require reseeding.

2. *Areas*

The Great Plains region has been divided in many ways by several writers to group more adequately factors that influence crop and plant adaptation, land use and management, and needed conservation practices. Three areas will be used in this presentation and designated as the northern, central, and southern Great Plains areas. These are essentially the areas designated by Barnes (1957), although he named the central area differently. According to Barnes (1957) the differences are based primarily on temperature as it affects the growing of cultivated crops, spring wheat, winter wheat, and cotton. The average frost-free periods in the northern, central, and southern areas are, respectively, 110–150, 130–200, and 180–300 days. These differences, combined with precipitation, erosion and runoff, and the complex commonly called photoperiodism, affect the adaptation and use of grasses and legumes.

3. *Developing Grasses and Legumes for Conservation Work*

The outstanding feature of the development of forage crops for conservation work in the Great Plains region has been the widespread use of native species. Cooper (1957) pointed out that native grasses had demonstrated their superior conservation effectiveness over exotic species in permanent seedings on land in the lower capability classes. He cited research results showing that the effectiveness of plant cover for reducing soil and water losses increased as it approached the climax composition for the site. Exotic species provided adequate cover only where artificial measures such as fertilization could be effectively used. No generally successful legumes have yet been found for reseeding or interplanting to improve the cover on land in the low capability classes.

On land in the higher capability classes, due to better soil conditions or more favorable climate or both, and on land that is cultivated, exotic grasses and legumes can be used for rotation pastures, green manure, cover cropping, and field windbreaks. Both native and exotic grasses are used for waterways and stabilization of embankments.

A second significant advance in the use of grasses in this region is the establishment of the principle that the area of full adaptation of ecotypes of native species may be relatively narrow. Cooper (1957) summarized the results of many field plantings and comparative evaluations and concluded that an ecotype can be moved a maximum of 300 miles north and 150 miles south of the point of origin to areas of comparable soil and climatic conditions and be expected to give satisfactory performance under natural conditions. He recognized that ecotypes of some species might have wider amplitude than others.

Many new exotic grasses and legumes have been introduced to the region. Several of them and several indigenous species have been improved by selection and breeding, and this has resulted in the extension of their range of adaptation.

An outstanding activity in the Great Plains region has been the extensive harvest of seed from native grass areas in soil conservation districts. Such harvests were made in years of favorable climate when a good set of seed was obtained. Hoover (1939), Hoover *et al.* (1947), and Cooper *et al.* (1957) described field machinery and harvesting methods and gave directions for processing seeds of native grasses. Modification of existing farm implements rather than construction of special devices was a feature of this work.

B. The Northern Great Plains Area

The northern Great Plains area was delineated and some of its features were described by Rogler and Hurtt (1948). Norum *et al.* (1957) modified

the boundaries slightly and described the effect of climate and soil on the agriculture of the area. The northern boundary of the area is 49°, and the southern boundary approximates 41° north latitude. The climate is arid and has wide extremes. Average annual precipitation varies from 10 to 27 inches from northwest to southeast and about three-fourths comes during the growing season, April to September. Severe and extended droughts have occurred. High summer and low winter temperatures give a range of more than 130° F. Norum *et al.* (1957) reported that broad zones of soil differ as do climate and natural vegetation.

About 25 per cent of the land in this area is under cultivation, but it is not evenly distributed. Much of the remaining area is grassland. A small but important percentage of the entire area is irrigated. Overextension of cultivation during periods of high prices followed by abandonment after several years of drought and wind erosion resulted in the large areas needing reseeding to grass as reported by McClymonds (1947). Overuse of rangeland and drought years also resulted in a decline in the condition of some of the native grasslands so that artificial restoration became necessary to obtain an effective cover for soil and water conservation and forage production.

Grasses and legumes for conservation work in the northern Great Plains area are of two kinds: exotic and native. Several exotic species have been widely used on land in the higher capability classes, especially those that are irrigated or used for intensive crop production. Some exotic species have been used to reseed abandoned farmlands and rangeland in poor condition. But, ecotypes and improved varieties of indigenous grasses have been widely and successfully used on these lands, as pointed out by Cooper (1957).

1. Grasses Widely Used

a. Exotic Grasses. Smooth brome (*Bromus inermis*) is widely used for hay and pasture on fertile cultivated land. Its use on nonirrigated land is primarily in the eastern portion of the area where rainfall is adequate. Several new varieties have been developed and released. LINCOLN and HOMESTEADER were developed from adventive stands in Nebraska and South Dakota, respectively. LYON is a variety developed from LINCOLN, and a more recent release called LANCASTER is a synthetic of several outstanding plants. These varieties have been registered, and the descriptions were given by Hein (1955a). All of them are of the southern type, and an outstanding quality in addition to forage and seed production is early spring growth. Early spring growth is of special advantage in an area where the grasses in native pastures are summer growers. Bromegrass is grown with alfalfa for hay and pasture in rotation with cultivated

crops. It is sometimes used in waterways and to protect other structures and may be grown alone in such cases.

Many thousands of acres of land in the semiarid portion of the northern Great Plains area have been seeded to crested wheatgrass (*Agropyron desertorum*). This drought-resistant, winter-hardy grass first came into prominence in this area and has been used extensively to reseed abandoned land in wind erosion areas and rangeland in poor condition. Ease of establishment, early spring growth, and persistence under grazing have contributed to its value. Pavlychenko (1941) and Woods *et al.* (1953) showed that the root system was extensive.

Crested wheatgrass is usually seeded alone on land in low capability classes, but McWilliams (1954) showed that it could be grown successfully with one or two other cool-season grasses under these conditions. McWilliams (1954) and Barnes and Nelson (1950) showed a clear advantage in production by growing crested wheatgrass with alfalfa where precipitation and soil conditions allowed the use of the legume. An improved variety of crested wheatgrass, NORDAN, was released and registered in 1955. The outstanding feature of the variety is greater seedling vigor, which increases establishment under the hazards of climate so often encountered in this area. Other characteristics of the variety are described by Rogler (1954) and Hein (1955c).

Intermediate wheatgrass (*Agropyron intermedium*) has recognized qualities as a forage plant and for soil conservation, and its use is increasing in the northern Great Plains area. It is winter hardy but is intermediate between crested wheatgrass and smooth brome in drought resistance and moisture requirement. An ideal combination for hay production is intermediate wheatgrass with alfalfa, because this grass matures later than the legume and its quality in the mixed hay is excellent. McWilliams (1954) grew this grass successfully with several other cool-season species but pointed out that alternate row seedings improved compatibility. Woods *et al.* (1953) presented data showing that intermediate wheatgrass exceeds smooth brome in conservation effectiveness. NEBRASKA 50 is the only improved variety that has been released. Ree wheatgrass is a mixture of intermediate wheatgrass and pubescent wheatgrass (*A. trichophorum*) that was released in 1945 in South Dakota. Its culture, use, and characteristics were described by Franzke (1945).

Russian wildrye (*Elymus junceus*) is another introduction that is included here because of its superlative conservation value. This bunchgrass has a dense mat of basal leaves and produces an unusually large amount of tough fibrous roots. It is entirely winter hardy and drought resistant when once established. No other exotic grass adapted to the area is as high in digestibility and nutritive value throughout the growing season.

The greatest usefulness of Russian wildrye is for grazing during seasons when other grasses are low in palatability and nutritive value. Rogler (1951) reported that it is adapted to a wide variety of soils but is most productive on fertile loams. It does not yield well on soils that are low in fertility unless there is sufficient moisture to allow the use of nitrogen fertilizers.

A major deterrent to the more general use of Russian wildrye in the northern Great Plains area is erratic seed production. Studies of cultural methods to increase and stabilize seed production have been made by Stitt (1954), Conard (1946), and McWilliams (1954). Regardless of the cultural methods used, the yield was relatively low.

b. Native Grasses. Four native grasses are useful in conservation work in the northern Great Plains. Two of them are cool-season grasses, and the others are classed as warm-season.

Western wheatgrass (*Agropyron smithii*) is widely distributed in the native vegetation throughout the northern Great Plains area and to the southward, as was shown by Hoover *et al.* (1947). The growth characteristics of this vigorous sod-forming grass include drought and winter hardiness, wide adaptability to soil and climatic conditions, and ability to spread rapidly by rhizomes. Hoover *et al.* (1947) pointed out that it volunteered soon after land was abandoned from wheat production. The vigorous rhizomes make the grass well suited to soil stabilization in waterways and on embankments and to the control of erosion on land in the lower capability classes. Short and Woolfolk (1952) stated that it is especially well adapted to heavy soils and survives submersion by flood waters.

Western wheatgrass makes good forage for grazing in spring and early summer and again in the fall. If the forage cures in the field a good quality of "standing hay" is available for winter grazing. Establishment by seeding is sometimes slow, and this has led to recommendations that it be seeded in mixtures, but the studies of McWilliams (1954) showed that western wheatgrass was not persistent in mixtures. McDermand (personal communication, 1957) stated that seed collected from native stands that were a mixture of western wheatgrass and green needlegrass (*Stipa viridula*) were in general use for permanent seedings on low capability land, waterways, and rangelands. No varieties of western wheatgrass have been released, but in conservation work there is advantage in following the principle of using locally collected seed as pointed out by Cooper (1957).

The center of distribution of green needlegrass coincides with that of western wheatgrass, as was illustrated by Hoover *et al.* (1947), but distribution is not as extensive. In adaptation to soils and resistance to flooding and inundation the two grasses are similar. Short and Woolfolk (1952) indicate that green needlegrass is good forage for grazing, especially in

summer. The grass is easy to establish and spreads from seed. McWilliams (1954) found that it had wide adaptation to date of seeding and was successful in mixtures with crested wheatgrass or Russian wildrye. GREEN STIPAGRASS is an improved variety of green needlegrass that is superior to others in general vigor, leafiness, and yield. The variety has been released and registered and was described by Rogler (1946) and Hein (1955d). McDermand (personal communication, 1957) stated that the use of GREEN STIPAGRASS in conservation work was increasing.

Switchgrass (*Panicum virgatum*) is a vigorous native perennial sod-forming grass that requires more moisture than western wheatgrass or GREEN STIPAGRASS and is most common in the eastern part of the area. Heavy, vigorous roots and underground stems, ease of establishment, and good seedling vigor make it an excellent grass for protecting waterways. It prefers heavy soil or lowland sites with high water tables but will survive short periods of drought. Cox (personal communication, 1957) reported that an improved strain, NEBRASKA 28, is widely used in the eastern part of the area for waterways, watershed structures, and permanent pasture mixtures on low capability lands. Keim and Newell (1951) state that palatability and nutritive value are rather low, but experience in the field shows that switchgrass is high in both qualities.

2. *Grasses for Special Uses*

Sand lovegrass (*Eragrostis trichodes*) is native to sandy lands in the area, especially to the Sandhills, where it is widely used to reseed poor-condition rangelands and abandoned farmlands. Hoover *et al.* (1947) report that this erect, vigorous bunchgrass begins growth early in the spring and remains green until late fall. It is easily established by seeding and is one of the best grasses to use on weed-infested abandoned land. It volunteers aggressively where grazing is managed to allow seed to form. Seed is not harvested from natural stands but is grown under cultivation. Cox (personal communication, 1957) stated that the strain designated as NEBRASKA 27 is preferred in conservation work.

Four exotic grasses have special-purpose uses in the northern Great Plains area according to reports by Cox, McDermand, and McWilliams (personal communications, 1957). These are commonly used in conservation work in other western states and are tall fescue, reed canarygrass, meadow foxtail, and tall wheatgrass. All are especially adapted to wet or poorly drained lands, and tall wheatgrass thrives on wet alkali soils.

A new grass called Stiporyzopsis, which is a natural hybrid between green needlegrass and Indian ricegrass, should become a valuable addition to the small number of grasses available to reseed sandy lands under

low rainfall conditions. This grass was described by Nielsen and Rogler (1952).

Mixtures of big, little, and sand bluestem (*Andropogon* sp.) seed are harvested from native stands in the Kansas Flinthills and southward and in and around the Sandhills in the southern part of the area. These mixtures are used for making permanent pasture seedings for erosion control and for reseeding poor condition ranges. Seed of big and little bluestem is also harvested from native stands in the central Great Plains area.

3. *Legumes in General Use*

Few legumes have yet been found that are broadly adapted for general use in conservation work in the northern Great Plains area. The lack of reliable legumes for forage and soil improvement on low capability farmland and on rangeland is one of the major plant problems of the area. Alfalfa and sweetclover are used on nonirrigated farmlands where the total annual precipitation is adequate for crop rotations. Barnes and Nelson (1950) and McWilliams (1954) obtained substantial increases in the yield of forage when alfalfa could be established with dryland grasses for permanent pasture. McWilliams obtained similar results with sweetclover, but they were temporary because the sweetclover did not reseed. Alfalfa is an important hay crop and is used in pasture mixtures on irrigated land. Red, white, and alsike clovers are also used in pastures. Only the winter-hardy alfalfas are well adapted. LADAK is the leading variety on nonirrigated land, and RANGER and VERNAL are used where irrigation is possible. Common yellow and MADRID sweetclovers are in general use, and a variety called GOLDEN TOP is recommended in South Dakota. Cox (personal communication, 1957) reported that MIDLAND and KENLAND red clover are used with phosphate fertilizers in the Sandhills.

C. The Central Great Plains Area

The central Great Plains area was delineated by Hobbs (1957), who called it the winter wheat and grazing region. Its northern and southern boundaries approximate 41° and 35° north latitudes, respectively. An area similar to this but slightly different in boundaries was described by Savage and Costello (1948). This area differs from the northern Great Plains area, having slightly more precipitation, a somewhat longer growing season, and less severe winter temperatures. Savage and Costello (1948) characterized the critical climatic conditions as highly variable with light rainfall, low humidity, and high winds. The principal agricultural crops on nonirrigated land are winter wheat and grain sorghum. Soils vary from dune sands to heavy clays, and the native vegetation of the entire area is grass. Large areas of this grassland were plowed for dryland wheat

production without reference to land capability for use and often without soil conservation practices. The area is subject to intermittent droughts, and some of them have been long in duration. Wind erosion under these conditions has been cataclysmic, resulting in extensive land abandonment. Drought and heavy grazing use caused serious decline in the condition of large acreages of rangeland so that these were subject to wind and water erosion. In the eastern part of the area torrential rains caused severe erosion, especially when crops were grown on sloping land with shallow soil.

Soil and water conservation measures are especially important in the area. Adjustment in land use, restoration of rangelands that are in poor condition, and water conservation all require the extensive use of grasses. Special cultural techniques, improved grass management methods, and improved varieties of grasses and legumes have been developed. The domestication and use of native grasses in conservation work has been singularly outstanding. The advances in this field have resulted from close cooperation between state and federal experiment stations and the plant materials technicians of the Soil Conservation Service.

1. *Grasses Widely Used*

Smooth brome is the most widely used tame grass in the conservation program when annual precipitation is adequate or the land is irrigated and well-drained fertile soils occur. The ACHENBACH variety, developed from an adventive stand and released in Kansas, was one of the first southern types to gain prominence. Atkins (personal communication, 1957) reported that the greater part of the 3 million pounds of smooth brome seed produced annually for the ten years prior to 1955 was ACHENBACH. Another variety, SOUTHLAND, that was released in Oklahoma in 1953 may extend the southern limits of smooth brome. This variety is a composite of eight lines selected from an old field that was originally planted with seed from Kansas. Smooth brome is used with alfalfa or Ladino clover for hay and pasture in rotation with cash crops.

Tall fescue, either KENTUCKY 31 or ALTA, is used in rotation pastures on slowly permeable soils south of the area of adaptation for smooth brome. Although a cool-season grass, it may be used as a year-long pasture where soil moisture is adequate.

Native grasses are widely used to make permanent seedings on land subject to erosion, to reseed abandoned land and rangelands in poor condition, and to protect structures designed for control of runoff water. Atkins (1957) stated that about 200,000 acres of such seedings were being made annually. Atkins (personal communication, 1957) reported the results from field trials that showed the superiority of western wheatgrass, switchgrass, and native grass mixtures over exotic grasses for sodding

waterways. Although seed of improved varieties of native species is being grown on irrigated lands, large quantities of seed are harvested from natural pastures, much of it by soil conservation districts. These seeds are mixed, and mixtures of commercially grown seed are also mixed for large-scale plantings.

Sideoats grama (*Bouteloua curtipendula*) in mixtures with other native species is widely adapted to the area for seeding abandoned cropland to permanent pasture, reseeding rangelands, and for permanent cover on waterway structures. Hoover *et al.* (1947) reported that seedlings are vigorous and stands are easy to establish on land in low capability classes or on eroded soils. Sideoats grama produces leafy forage that is palatable to livestock. The EL RENO variety was developed from an ecotype collected by plant materials technicians of the Soil Conservation Service in Oklahoma and was released for certification in Kansas in 1944. The CORONADO variety developed from a New Mexico ecotype was released for certification in Oklahoma in 1956.

BLACKWELL switchgrass was developed from an Oklahoma ecotype of *Panicum virgatum* and released for certification in Kansas in 1944. Its range of adaptation and uses in conservation work coincide with those of sideoats grama, but it has heavy, vigorous roots and underground stems. This variety is leafier, has finer stems, and has given higher forage and seed yields than other switchgrasses. The CADDO variety was released for certification in Oklahoma in 1956 and may supplement BLACKWELL in the southern part of the area. A synoptic description of these two varieties was given by Wheeler and Hill (1957), and their development illustrates the principles of adaptation of ecotypes of native species given by Cooper (1957).

Sand lovegrass (*Eragrostis trichodes*) is used for reseeding sandy land in the western part of the area in the same way that it is used on such land in the northern Great Plains area. Atkins (personal communication, 1957) reported that this grass is adversely affected by extended periods of drought when grown where average annual precipitation is less than 20 inches. He also reported that seed was grown on many farms in soil conservation districts, but no improved varieties have been released. He regarded it as an important grass to use in mixtures for planting sandy lands.

Sand bluestem (*Andropogon hallii*) and Indiangrass (*Sorghastrum nutans*) occur naturally on deep sandy soils of the area in mixtures with other native grasses and are used for seeding permanent pastures on such lands. They are easy to establish and are palatable to livestock. Some new varieties are being developed, but at present seed is harvested from native stands and is mixed with other species.

2. *Grasses for Special Uses*

Several grasses have shown promise for reseeding, waterway protection, and erosion control in the area but have been restricted in use for several reasons. Some are exotic but most of them native to the area. Varieties have been developed for a majority of them.

Crested wheatgrass and western wheatgrass are cool-season grasses used for permanent seedings in the northwestern part of the area, although western wheatgrass is used for waterways in other portions, as was shown by Atkins (1957). Intermediate wheatgrass has been used to some extent in tame grass pastures in the northwestern portion of the area and to the eastward during years of favorable moisture. However, it has been used on lower capability land and has not had the intensive management that it requires; hence, it has not given satisfactory performance. The use of cool-season grasses would have advantage in extending the grazing season, but Savage *et al.* (1948) pointed out that the native warm-season grasses retain their nutrients during the winter to a remarkable degree.

Because seed is difficult to harvest or production of improved varieties has lagged, the KAW variety of big bluestem (*Andropogon gerardi*), Caucasian bluestem (*A. caucasicus*), and the HAYS variety of buffalograss (*Buchloe dactyloides*) are not yet used to the extent that these grasses merit. Big bluestem and buffalo seed on the commercial markets are harvested from native stands in years when good sets of seed are produced. HAYS buffalograss was released in Kansas in 1944, and KAW big bluestem was released in 1950. Buffalograss provides excellent erosion control and pasture on rangelands with heavy soils, and big bluestem with deep roots and short rhizomes produces an erosion-resisting sod and is useful in converting cropland to meadows and pastures and in seeding waterways. Caucasian bluestem provides a quick cover in waterways and on the embankments of watershed protection structures when seeded in mixtures with other native grasses.

New varieties of two exotic grasses and four native species have merit but have been released only recently and therefore are not in general use. SOUTHLAND smooth brome has already been described. MIDLAND Bermudagrass, described by Harlan *et al.* (1954), is a hybrid between COASTAL Bermuda and a hardy variety from Indiana. It is not quite as vigorous as COASTAL but is more winter hardy. The use of this variety is for pasture, waterways, and watershed protection structures. High fertility and good grazing management are necessary for good yields. WOODWARD sand bluestem, released in Kansas in 1956 and in Oklahoma in 1957, and CADDO switchgrass, released in Oklahoma in 1956, should come into use, re-

spectively, for range seedings on sandy land and waterway seedings as soon as seed supplies are adequate.

Tall wheatgrass has special use in the northern part of the area where Atkins (personal communication, 1957) reported several hundred thousand acres of saline land that cannot be drained. Its adaptation to such conditions is the same as described for the northern Great Plains area. It is also used in waterways in the southern part of the area where alkali "spots" have caused other grasses to fail. EL KAN bluestem, a variety of *Andropogon ischaemum* found in 1937 as a stand adventive in Kansas from seed traced to Texas sources, is winter hardy to the northern part of the central Great Plains area. It is used to produce an erosion-control cover on watershed protection structures.

3. *Special Cultural Methods*

Special cultural methods and seeding and machinery have been developed to plant native grasses successfully under the stringent climatic conditions and erosion hazards in the western part of the area. These and machinery for harvesting and processing seed have been described by Hoover *et al.* (1947), Savage *et al.* (1948), Stoesz (1952), and Cooper *et al.* (1957). Seeding into stubble mulch or the stubble of Sudangrass or grain sorghums has been successful in wind erosion areas and where excessive evaporation is likely to occur. Elsewhere in the area, and on higher capability land, conventional methods of good seedbed preparation are followed. Special drills to plant chaffy or very small grass seeds have been devised, and modifications of grain binders and combines have been made to harvest seed of native grasses. Several soil conservation districts own such special machinery for use by cooperating farmers.

4. *Legumes in General Use*

Legumes that give reliable stands under the scanty and variable precipitation and other limiting factors in the western part of the area have not been developed. In this respect the central Great Plains area has the same problem as the northern Great Plains area. On good farmland in the higher capability classes, alfalfa and sweetclover provide hay and pasture, and Ladino, white, red, and alsike clover are used in irrigated pastures. BUFFALO alfalfa in the northern part of the area and OKLAHOMA common alfalfa in the southern part are leading varieties. MADRID has the widest adaptation among sweetclover varieties. Some Korean lespedeza is planted with summer grasses in the eastern part of the area.

D. The Southern Great Plains Area

The southern Great Plains area is large and has wide variation in climatic and edaphic conditions. Its northern and southern boundaries approximate 35° and 28° north latitudes, respectively. Allred and Nixon (1955) estimated that it covered about 117 million acres. All of the region was once grassland, and approximately one-third has been plowed and used for crop production.

Johnston (1957) described the features of climate, topography, and soils that affect crop production. They differ from the other two areas in the Great Plains region primarily in having higher average temperature, a longer growing season, and a greater variety of soils. The climate is mild enough for cotton; however, there is a wide variation in temperature and precipitation from season to season and from year to year. The soils vary from slightly acid to calcareous and from deep sands and clays to thin soils. Erosion varies with climate and soil. Wind erosion is common in the western half of the area and in drought years is severe. Water erosion and gullying occur on two-thirds of the area and are most serious in the eastern third where high intensity rains occur. Water conservation measures are important on all land because evaporation rates are high.

A large number of grasses are needed in such a diverse area to conserve moisture effectively, control runoff and wind and water erosion, maintain and improve soil structure, and reseed rangelands. Allred and Nixon (1955) pointed out the importance of knowing the land capability classes to determine land use and to select the grasses and legumes for conservation seedings. Seed of adapted species and varieties is needed in quantity because these authors pointed out that 6 million acres of land now in cultivation needed to be seeded to grass, 25 million acres of cropland required grasses and legumes in rotations, nearly 2 million acres of rangeland should be overseeded, 24,000 miles of waterways required grass cover, and more than 33,000 dams and spillways needed to be stabilized. In addition to these needs for land treatment for conservation of soil and water, some of the 112 million acres of rangeland now infested with mesquite and other shrubs will require reseeding where the invading shrubs are cleared by mechanical means or herbicides.

Most of the grasses used in the area are warm-season species. They are almost equally divided between native and exotic species. Some new varieties are in use, and seed of these and of recognized ecotypes of native grasses is grown under cultivation. Large quantities of seed have been harvested from native stands by soil conservation districts.

1. *Grasses Widely Used*

Introduced grasses that are widely used in conservation work in the area are blue panicum (*Panicum antidotale*), weeping lovegrass (*Eragrostis curvula*), Turkestan bluestem (*Andropogon ischaemum*), and buffelgrass (*Pennisetum ciliare*).

Blue panicum is a vigorous, robust grass that reaches a height of 5 to 7 feet on land in the high capability classes. Root production is heavy and yields of forage are high on good land, especially when nitrogen fertilizer is used. Excellent silage and good hay are made from this grass, and grazing capacity in pastures is high when adequate regrowth periods are provided. Harlan (1952) stated that it should be considered as a tame pasture grass rather than a range grass. However, Smith (1956) reported that it is being used successfully for reseeding rangeland from which invading brush has been cleared. It is used in crop rotations on good land with irrigation in the western part of the area, and Cooper (personal communication, 1957) reported the use of blue panicum for wind strips in cultivated fields. Excellent yields of seed are obtained on irrigated land.

Weeping lovegrass with its adaptation to low capability lands, dense root production, and ability to spread by seeding is used to provide cover on eroded sites and embankments. At least 20 inches of rainfall is required for satisfactory stands and survival. Staten and Elwell (1944) reported its use for stabilizing waterways on sloping land with high speeds of flow, but Ree (1952) cautioned against using this grass on slopes above 5 per cent and a permissible velocity of 3.5 feet per second.

KING RANCH bluestem was developed from an adventive stand of Turkestan bluestem and is the only strain of the species that is widely used in the area. The other named variety, EL KAN, was adventive in Kansas and is more cold resistant but not as productive as KING RANCH in the southern Great Plains area. KING RANCH bluestem is used for soil improvement in rotation with cash crops, for overseeding on rangelands, for vegetating waterways, and to stabilize embankments on watershed structures and tankdams. It is adapted to a wide range of soils in the western half of the area. The qualities that make it useful in conservation work are prolific seed production, ease of establishment to a good, quick ground cover, and an extensive deep root system. Seed harvest is somewhat difficult, but Hoover *et al.* (1947) describe methods that are satisfactory. Seed is chaffy and can be processed or planted with special seeders that are used in soil conservation districts and were described by Allred and Nixon (1955). Forage qualities of KING RANCH bluestem are good, and it is palatable.

Buffelgrass is still relatively new to the area but is gaining in popularity since seed has been produced commercially. Its primary uses are reseeding

of low capability farmlands and overseeding rangelands in poor condition. Smith (1956) reported the use of buffelgrass for seeding rangelands from which brush had been cleared. The exact range of adaptation has not been established; however, its northern limit is approximately at 33° latitude. It has grown on a wide variety of soils but has done best on sandy soils, even in the drier western portion of the area. It is sensitive to low temperatures and may behave as an annual near the northern part of the area. Established stands survive at least short periods of drought. Seedings of buffelgrass are readily established in warm, wet weather, and plants grow rapidly and produce seed quickly. Flowering is indeterminate and this complicates seed harvest, but vacuum harvesters can be used with row plantings. Plants that have produced seed are especially early in spring recovery the following season. Palatability is very good. There are two strains, and these are designated by the Soil Conservation Service numbers T-4464 and T-3782. The first is known as buffelgrass and is in commercial production. The second is known as blue buffelgrass. Wheeler and Hill (1957) describe these strains. Blue buffelgrass differs from buffelgrass in that it has shallow rootstalks by which the grass spreads, is more tolerant of temperatures below 10° F., and is adapted to heavy clay soils.

Eight native grasses are used extensively in conservation seedings in the area. All are warm-season species; two spread by strong rhizomes, and the others are bunchgrasses. Five of these species were used in the central Great Plains area. All of them are effective in conservation seedings because they form a dense turf and have extensive soil-binding root systems. Their greatest usefulness has been for permanent seedings to convert abandoned and seriously eroded cropland in low capability classes to pasture and to overseed rangelands in poor condition.

Seed of native grasses for use in conservation is obtained by direct harvest from natural stands in most of the cases. Therefore, seed is often mixed. For example, sand lovegrass occurs with sideoats and blue grama. Blue grama also occurs with sideoats grama and buffalograss. The differences in these combinations reflect differences in climatic and soil conditions. When harvests of seed are made from native stands there is advantage in using them near the area of occurrence. Seed of some grasses is grown commercially, especially when improved varieties have been released or where harvest from native stands is difficult. Examples of these two cases are BLACKWELL switchgrass and sand lovegrass. An excellent tabulation of mixtures of native grasses for conservation use was presented by Allred and Nixon (1955). They listed 10 native grasses and suggested those that are or should be used together on each of the 8 subareas delineated by Johnston (1957). Allred and Nixon divided 2 of the subareas further according to the major kinds of soil.

The characteristics of sideoats grama, BLACKWELL switchgrass, sand lovegrass, sand bluestem, and Indiangrass for erosion control and forage have been discussed in the section on the central Great Plains area. In the southern Great Plains area sideoats grama, sand lovegrass, and sand bluestem are used in the western half and BLACKWELL switchgrass and Indiangrass are used primarily in the eastern half of the area. The mixtures in which they are used were given by Allred and Nixon (1955). Smith (personal communication, 1957) gave preference for the WOODWARD variety of sand bluestem in the southern Great Plains area.

Blue grama (*Bouteloua gracilis*) and buffalograss (*Buchloe dactyloides*) are components of mixtures in the southern Great Plains area. Blue grama is a bunchgrass and buffalograss spreads by surface runners, and they often occur together in native stands. Both establish easily, and Hoover *et al.* (1947) state that blue grama is one of the most dependable native grasses for conservation use. They are both used primarily in the western part of the area on deep and shallow clay soils (hard lands) and on loamy soils. Sideoats grama can be mixed with them. All of these grasses are excellent forage, and blue grama is especially palatable and retains its nutrients to make good standing hay.

Little bluestem (*Andropogon scoparius*) occurs naturally with big bluestem in the northern part of the area but is found on lower capability lands due to coarse soil, steep slopes, or droughty conditions. It is a bunchgrass with a deep fibrous root system and is used in crop rotations and in mixtures for reseeding land in low capability classes to pasture. Sideoats grama, sand bluestem, Indiangrass, and sometimes big bluestem, are components of the mixtures. Little bluestem has relatively low palatability unless it is carefully managed to avoid large amounts of coarse growth. Seed is successfully harvested from native stands but has also been grown successfully under cultivation. No new varieties have been developed, and, since the species occurs over a wide area, seed collected locally would be better adapted for use in permanent pastures.

2. *Grasses for Special Uses*

MEDIO bluestem is a variety of Angleton bluestem (*Andropogon nodosus*) that was developed from an adventive stand discovered by technicians of the Soil Conservation Service. It is more vigorous and more palatable, has a longer growing season, and is adapted to lower rainfall areas than common Angleton bluestem but resembles it in leafiness, excellent root production, and rooting at the nodes of trailing stems to form a dense turf. It is especially useful in waterway seedings where it can be established either from seed, sprigs, or rooted runners. Extensive use is made

of vegetated waterways in the eastern half of the area. MEDIO bluestem has promise for reseeding rangelands in the same part of the area.

The use of blue panicum for field windbreaks in areas where cotton is grown without irrigation has been mentioned. Napiergrass (*Pennisetum purpureum*) is used for the same purpose, and this grass is also grown to a limited extent for green chop for dairy cattle. Its well-known sensitivity to low temperature confines it to the warmer southern part of the area, and maximum production is obtained only on good land.

COASTAL Bermuda that was developed for the Southeastern region is well adapted for pasture on lands in the higher capability classes in the eastern part of the southern Great Plains area. Fertilizers and good grazing management are needed for maximum production. Near the northern part of the area MIDLAND Bermuda can be used if low temperatures are unfavorable to COASTAL. COASTAL Bermuda can be used in waterways if the fertility level of the soil is high and the stand is grazed. Common Bermuda can be used when conditions are not favorable for COASTAL, and Ree (1952) found that it was well suited to this use. Beck (1957) described the size and extent of waterway construction, especially in the portion of the area commonly called the Blacklands, and indicated the extensive use of Bermudagrass for protective sod cover. In addition, common Bermuda can be used to stabilize pond dams, spillways, and roadsides.

3. *Legumes*

Satisfactory perennial legumes for permanent pasture seedings on land in the low capability classes or for overseeding rangelands in this area have not been found. Legumes are useful in crop rotations on farmlands. A pronounced influence on row crops that follow legumes in the rotation has been established in this area. For example, Johnston (1957) reported results from several experiments where the row crops failed to respond to fertilizers following legumes.

Legumes in widespread use in crop rotations designed for soil conservation and improvement are alfalfa, sweetclover, lespedeza, and vetch. Nonhardy alfalfas are used in both long and short rotations on irrigated lands in the western part of the area. The length of the rotation depends on the land capability class. Sweetclover is used in many rotations in the eastern part of the area. HUBAM, EVERGREEN, and MADRID are preferred varieties. The sweetclover is sometimes grazed before it is plowed. Sericea lespedeza, with or without grass, is used in the eastern part of the area. If alfalfa is used here it must be limed. Hairy vetch and rye are recommended winter cover crops. The local production of vetch seed has recently proved successful. All legumes respond to phosphate fertilizers, and the effect of using it is reported to carry over to the succeeding crop.

White, red, and crimson clovers are widely used in pastures on cultivated land either where rainfall is adequate or under irrigation.

4. Cultural Methods

The cultural techniques for establishing grass on low capability land classes, especially where the hazard of wind erosion is high, that were developed and are used in this area are similar to those in the central Great Plains area. Seeding into the stubble of grain sorghums or Sudangrass is a common practice. The use of redesigned or special seeders and drills for planting trashy seed of many native grasses or seeds that are especially small is general throughout the area. Many modifications of binders and combines have been made to harvest grass seed from native stands. Several soil conservation districts own such machinery for use by their cooperators. All of these developments have contributed to the rate at which land is being protected from erosion, and water is conserved with effective cover of adapted grasses.

V. The Western Region

A. Description

The Western region includes all of the country west of the Continental Divide, but the discussion will exclude forested lands. It is a large region and, for the purpose of this discussion, is divided into two general areas, the coastal and the intermountain, and each of these will be divided into north and south. The coastal area lies between the Cascade-Sierra Nevada Mountains and the ocean. The north coastal area includes all of western Oregon and western Washington and a portion of northern California; the remainder will be referred to as the south coastal area. The intermountain area will be divided into north and south by a line approximating the northern boundary of Arizona and New Mexico.

Christ (1947) pointed out that a wide variety of conditions influence land capability for use and land treatment for conservation in the large and diverse Western region. Annual precipitation varies from 5 to 100 inches, and farming and ranching is carried on from below sea level to 6,000 feet above sea level. A large part of the region is arid; hence, a high percentage of the cropland is irrigated, and water conservation is important. The nonarable portions of the arid lands are used for range. Rainfall in the north coastal and part of the northern intermountain area is sufficient for crop production without irrigation. Climate is greatly and often abruptly modified by topography, as was shown by Bailey (1941). Topography influences total precipitation and its seasonal distribution and

modifies the length of the growing season. A wide variety of soils is found. Combinations of all these factors occur, making the region one of extremes, with complex problems for designing soil and water conservation measures.

The complex conditions make it necessary to use a large number of grasses and legumes. Many new exotic species have been introduced, and several native species have been domesticated for conservation work during the past 25 years. They are used for erosion control, watershed protection, soil improvement, and forage on cultivated lands; for reseeding rangelands; and for stabilizing problem areas.

Schwendiman and Hafenrichter (1955) explained the methods used by the Soil Conservation Service in cooperation with state experiment stations and other federal agencies for assembling and testing new plants for specific conservation uses, for determining their cultural and management requirements, and for getting new varieties into production under certification.

Water is the key to land use and production in the Western region, as was shown by Stewart (1948). The amount and distribution of precipitation and the use of irrigation or supplemental seasonal irrigation on cropland in all four of the subareas make it convenient to show the performance of grasses and legumes on irrigated, subhumid, and semiarid lands.

B. Grasses and Legumes for Conservation

1. *Irrigated Lands*

Hay and pasture crops are grown extensively on irrigated lands in the Western region. They are used to control erosion and to improve soil structure and fertility. They are grown in rotation with other field crops unless some land capability condition such as shallow soil, poor drainage, and salinity or alkalinity is limiting. The yield from forage crops in rotation can be high when improved varieties, good water management, and proper cultural practices are used.

a. Hay. Alfalfa is widely used for hay on irrigated lands where soil depth is adequate, drainage is good, and saline or alkali conditions are not excessive. Its value for forage and for soil improvement has long been recognized. Growing grass with alfalfa has been observed to increase the conservation effectiveness of the hay crop, and Jackobs (1952) showed that grass prevented the invasion of weeds. The mixture was not readily accepted on the market, but Keith *et al.* (1950) fed mixtures to sheep in comparison with alfalfa and showed that there was no significant difference in gains, even if the mixture contained 30 per cent by weight of smooth

brome. Pair (personal communication, 1957) has preliminary information indicating some advantage to the management of irrigation water following the plowing down of alfalfa-grass mixtures. When limiting land capability conditions preclude the use of alfalfa, alsike or red clover or birdsfoot trefoil are substituted. These legumes are usually mixed with grasses.

Typical legume-grass mixtures for hay were outlined by Hafenrichter (1951). Smooth brome, orchardgrass, or intermediate wheatgrass are mixed with alfalfa on deep fertile soils where the supply of irrigation water is adequate. Tall fescue is used with alsike or red clover on shallow or poorly drained soils. When there is a shortage of water, intermediate wheatgrass or smooth brome and crested wheat are planted with alfalfa on deep, well-drained soils. Birdsfoot trefoil and meadow foxtail or tall fescue are good mixtures for poorly drained soils that are flooded part of the year. These mixtures are used in the northern intermountain area.

Varieties of legumes and grasses are important in irrigated hay mixtures. The winter-hardy and wilt-resistant varieties of alfalfa, RANGER and VERNAL, are used in the northern intermountain area; and a new aphid-resistant variety, LAHONTAN, is coming into use where the insect occurs. Nonhardy alfalfas, CALIVERDE, CHILEAN 21-5, and AFRICAN, are used in the southern part of the region, and MOAPA was recently released as an aphid-resistant variety. When red clover is planted in hay mixtures in the north Intermountain area, it is the same variety that is grown commercially for seed. KENLAND and, more recently, PENNSCOTT are the varieties being grown for seed. CASCADE, a broadleaf birdsfoot trefoil, is coming into use in the northern part of the region.

Varieties of grasses used in irrigated hay mixtures are MANCHAR brome, GREENAR wheatgrass, and ALTA fescue. MANCHAR brome was described by Stark and Klages (1949). It is leafy, carries its leaves well up on the stems, and has mild sod-forming characteristics. It is one of the northern types that was selected because it begins growth later in the spring and grows into early summer. These characteristics are desirable in the Western region in areas where smooth brome is adapted. GREENAR wheatgrass was described by Schwendiman (1956). Seedling vigor, freedom from disease, a long-growing season, good yields of forage and seed, compatibility with alfalfa, and good yields of roots are the important characteristics. MANCHAR brome and GREENAR wheatgrass require high capability land for good production. When restricted drainage or alkali soils are encountered, ALTA fescue is used. This variety was described by Rampton (1945). LATAR, a new variety of orchardgrass, has been released and is promising in alfalfa-grass mixtures for hay on irrigated land. It is described in the next section.

b. Pastures. Pastures on irrigated lands in the Western region are excellent for soil conservation. Season-long irrigated pastures in this region have an important role in assisting with the application of conservation on rangelands, as was pointed out by Hafenrichter (1957). A high percentage of the irrigated pastures are rotated with cash crops, and, because improved varieties of grasses and legumes are used, the grazing capacity is high if good management is practiced. Permanent pastures are used only when the land capability conditions are limiting, and cultivation should be infrequent. Among these conditions are shallow soils, light soils, steep land, poor drainage, and excessive salinity or alkalinity.

A few of the many grasses and legumes used in pasture mixtures have wide adaptation. During the past twenty years new varieties and strains of these species have been developed for specific conditions within the area of general adaptation. The new species that have been introduced for use in pastures are also represented by improved selections.

There has been a general trend toward simplifying irrigated pasture mixtures. One or two grasses with one or two legumes is the general rule. Chapin *et al.* (1955) showed that complex mixtures were less productive than simple mixtures and that only a few of the species in the complex mixtures were retained in the stand after 3 or 4 years of use. However, Bateman and Keller (1956) were able to show advantages from complex mixtures on high capability land when good management was used.

Cool weather perennial grasses and winter-hardy legumes are the basis of irrigated pasture mixtures in the northern part of the region. Summer-growing grasses and some cool-season grasses are used in the southern part of the region. Rapid-developing but relatively short-lived grasses and legumes are sometimes added to mixtures, but they may have an adverse effect on production. The data of Chapin *et al.* (1955) show that these grasses reduced the density of long-lived grasses and of white clover.

Two common grasses have wide adaptation for use in irrigated pastures: tall fescue (*Festuca arundinacea*) and orchardgrass (*Dactylis glomerata*). Tall fescue has wide adaptation to soil conditions as measured by differences in internal drainage and pH, but, as shown by Richards and Hawk (1945) and Bateman and Keller (1956), it is lower in relative palatability than most other pasture grasses. ALTA fescue is used in the north, but the recently developed GOARS fescue has been superior in the southern areas where summer temperatures are high. Both varieties are well adapted to poorly drained and wet saline or alkali soils in their respective areas of adaptation. The performance of GOARS fescue in pastures under these conditions when grazed by dairy cattle was described by Hafenrichter (1953).

Orchardgrass requires well-drained fertile soils and does not perform well when high temperatures obtain. Hence, it is used on the higher capability lands in the cooler parts of the region. The characteristics, adaptation, and use of the AKAROA variety in the coastal area are described by Hafenrichter *et al.* (1949). S-143 from the Welsh Plant Breeding Station is widely used in the northern part of the intermountain area. A new variety, LATAR, was just released jointly by the Soil Conservation Service and the Idaho and Washington Agricultural Experiment Stations. It is 10 days later than other varieties and has an abundance of light green leaves. It is a selection from an introduced accession obtained from the U.S.S.R. in 1935. Studies at the Washington Agricultural Experiment Station show that LATAR is lower in lignin content and higher in digestibility than other varieties, and this is the first record of such a difference among varieties within a species. Field experience indicates winter hardiness, high yield, rapid recovery after cutting or grazing, greater palatability, and more suitable maturity for use with alfalfa as hay.

MANCHAR smooth brome is a component of some irrigated pastures. It requires well-drained fertile soils and is limited to the cooler portions of the northern intermountain area. There is now some indication that a new selection from one of the southern varieties may extend the range of use of bromegrass into warmer parts of the area.

The ryegrasses, domestic or common (*Lolium italicum*) and perennial (*L. perenne*), were once widely used in pasture mixtures to provide first-season grazing. They are still used in many mixtures, but they may have an adverse effect on production (Chapin *et al.*, 1955). PRAIRIE brome (*Bromus catharticus*) is now used in conservation mixtures in place of ryegrass in the southern part of the coastal area. It provides first-season grazing and ground cover but has not reduced the density of other grasses or legumes in the stand. However, it does require deep, well-drained, and fertile soils. TUALATIN oatgrass, described by Hein (1955e) and Wheeler and Hill (1957), is often added to pasture mixtures. It is persistent when good grazing management methods are used.

Kentucky bluegrass (*Poa pratensis*) is adventive in the northern part of the Western region and often invades poorly managed irrigated pastures. It is remarkably tolerant of poor management, low fertility, and restricted drainage, but Bateman and Keller (1956) showed that production is low. This grass can be used to protect land in low capability classes that are difficult to cultivate and hard to irrigate.

Bermudagrass (*Cynodon dactylon*) and blue panicum (*Panicum antidotale*) are warm-season grasses that are used in pastures in the southern parts of the Western region. COASTAL Bermuda, as described by Burton (1951), and blue panicum both have high grazing capacity under irriga-

tion on fertile soils. Both show good response to high rates of nitrogen fertilization. COASTAL Bermuda is tolerant of saline and moderately alkali conditions. Blue panicum must be grazed carefully because production and vigor have been observed to be adversely affected by frequent and close grazing. Both grasses produce an abundance of roots under good management. Common Bermuda invades poorly managed pastures and is much lower in production than COASTAL.

Tall wheatgrass (*Agropyron elongatum*) is widely used in conservation work on saline and alkali soils in the intermountain area of the West. This new introduction produces high yields of forage under extreme conditions of salinity and alkalinity, especially when adequately irrigated and fertilized with nitrogen. It has a long growing season and is both cold tolerant and resistant to high temperatures. The forage appears coarse, but palatability to livestock was found by Richards and Hawk (1945) to be surprisingly high. Good chopped hay and excellent silage are made from this grass. When tall wheatgrass is properly grazed, it retains its vigor and is persistent. Seedlings of this grass develop slowly on saline and alkali soils and must have frequent irrigation during the establishment period if good stands are obtained. Effective cultural methods for establishment under these conditions were described by Hafenrichter (1956).

The most widely used legume in irrigated pastures in the Western region is Ladino clover (*Trifolium repens latum*). Other long-lived legumes have been substituted only when severe winter conditions; long, hot summers; limited irrigation water; or excessive alkali obtain. White clover (*T. repens*) is adventive but is planted in areas where severe winters or shortage of irrigation water preclude the use of Ladino clover. Alfalfa is more winter hardy and more heat and drought resistant than Ladino clover and can be used in place of it when these qualities are needed. Narrowleaf birdsfoot trefoil (*Lotus tenuis*) is well adapted to alkali conditions. The performance of the LOS BANOS strain with GOARS tall fescue was described by Hafenrichter (1953). Strawberry clover (*T. fragiferum*) is sometimes used under these conditions, and the PALESTINE variety has given better yields than common. Red and alsike clover are sometimes added to mixtures in areas where they are adapted.

The value of alfalfa in irrigated pastures is being recognized where land capability conditions permit its use. The data of Bateman and Keller (1956) show that yields of irrigated pastures can be increased by using it as the principal legume in the mixture. The work of Hagan and Peterson (1953) shows that alfalfa mixtures are high in yield when the method of grazing provides long regrowth periods. This method also reduces the hazard of bloat that has prejudiced graziers against using this legume in pastures. Broadleaved birdsfoot trefoil (*Lotus corniculatus*) responds to

the same management method and has the advantage of not causing bloat.

The management of irrigated pastures affects the adaptation of species, the floristic composition of mixtures, grazing capacity, and consumptive use of water. Hafenrichter (1957) reviewed the advances in pasture management in the Western region and pointed out the advantages of good methods. The more important management methods are choice of mixtures, especially with respect to land capability conditions, use of manures and fertilizers, system of grazing, and method of irrigation. Good composition and high yields are obtained when the better methods are applied.

Water conservation is important in many parts of the region, especially when supplies of water are short or the cost is high. The work of Hagan and Peterson (1953) made an important contribution to water conservation. They showed that consumptive use of water by pastures remained constant regardless of yield so long as adequate ground cover was maintained and that management methods to obtain high yield did not increase consumptive use. Another promising contribution to conservation of irrigation water for pastures is the work of Keller (1953), who showed that some genotypes of orchardgrass have a significantly lower water requirement than others.

2. *Grasses for Subhumid Conditions*

Subhumid conditions in the Western region are found on land receiving no less than 15 inches of precipitation annually. Crops are grown without irrigation or with supplemental irrigation in the summer. The upper limit of precipitation is 30 to 40 inches in the intermountain area and 60 to 70 inches in the north Pacific coast area. The predominant pattern of climate is winter wet and summer dry, except in the southern intermountain area where summer and winter rains are interspersed with rainless spring and fall seasons and summer rains predominate.

Soil erosion has been severe in the subhumid intermountain area and in many places in the coastal area, because much of the land is relatively steep. Some lands have drainage problems. Hay and pasture crops are used extensively. Most of them are grown in rotations with cash crops, and the length of time they remain on the land in a rotation cycle is determined by the land capability class and the farming enterprise. There is a tendency toward general-purpose grass-legume mixtures that can be used for pasture, hay, and silage.

Several of the grasses and legumes in the subhumid areas are those used on irrigated lands. LATAR, AKAROA, S-143, or common orchardgrass; MANCHAR brome; ALTA fescue; and TUALATIN oatgrass are grown in mix-

tures with alfalfa, one of the trefoils, or one of the clovers. Land capabilities, particularly those associated with soil depth, texture, fertility, and drainage, determine the combinations that are used.

Many new grasses have been developed for conservation work in the subhumid area. Some were introduced, and others were domesticated from native stands.

GREENAR wheatgrass is used with alfalfa in rotation with grain and peas on moderately steep and fertile but well-drained soils in the intermountain area. This variety is a selection from an introduction. The introduction, P.I. 58,568, its adaptation, and its use in conservation work were described by Hafenrichter *et al.* (1949) and the variety by Schwendiman (1956). Woods *et al.* (1953) found that the GREENAR-alfalfa mixture provided an especially good ground cover for erosion control and produced good yields of high-quality hay. They also showed that GREENAR wheatgrass produced a high tonnage of roots when grown in mixtures with alfalfa and pointed out the value of this characteristic for soil conservation. Its high value as pasture for beef cattle has been established by Galgan *et al.* (1953).

PRIMAR, a variety of slender wheatgrass (*Agropyron trachycaulum*), and BROMAR, a variety of mountain brome (*Bromus marginatus*), were both selected from ecotypes in the native vegetation specifically for use in soil conservation work. PRIMAR was described by Schwendiman and Law (1946) and BROMAR by Law and Schwendiman (1946). These varieties of rapid-developing grasses were selected for their compatibility with SPANISH and other sweetclovers. The mixtures are used in short rotations with grains and peas for erosion control and improvement of soil fertility and structure. They are either plowed down as green manure or pastured and then plowed. Schwendiman *et al.* (1953) found that mixtures of these grasses with sweetclover always produced better ground cover for erosion control and more roots for soil improvement than sweetclover alone. The production of forage by these mixtures was high; so at least one-half could be used for grazing without reducing the conservation effectiveness.

DRUMMOND is a late-maturing variety of timothy (*Phleum pratense*). It is a leafy variety that was developed at MacDonald College, McGill University, and introduced from Canada into the northern part of the coastal area by the Soil Conservation Service, primarily for use with MONTGOMERY red clover as hay and silage in short rotations. This grass-legume combination can be harvested during the rainless early July weather and thus cured as good hay. This is 3 weeks after other commonly used hay crops are cut and often spoiled by late spring rains. Good hay crops make it possible to design effective rotations for soil and water con-

servation. The use of DRUMMOND timothy is being extended to the northern intermountain area.

Meadow foxtail (*Alopecurus pratensis*) and reed canarygrass (*Phalaris arundinacea*) are used in poorly drained areas. An introduced strain of creeping foxtail (*A. arundinaceus*) has shown some superiority over meadow foxtail in the northern part of the region. These grasses provide excellent pasture and silage on lands that are not easily drained. Reed canarygrass is also used for pasture on tidelands along the ocean and to control deep waterways in the interior. No special strains are yet in use.

Several perennial grasses have promise for use in soil conservation work in the subhumid areas. A dwarf orchardgrass provides an effective but low-growing ground cover for use in orchards on sloping land, especially under irrigation. Meadow brome (*Bromus erectus*) is a bunchgrass with exceptionally high root production and adaptation to coarse soils and lands with dual use for grazing and timber. A vigorous variety of bulbous bluegrass (*Poa bulbosa*), a drought-tolerant sheep fescue (*Festuca ovina*), and a domesticated ecotype of Canby bluegrass (*P. canbyi*) are in limited use for understory ground cover in permanent seedings of grass on low capability lands. Creeping foxtail has stronger rhizomes than meadow foxtail, is leafy, and has awnless seeds. An ecotype of the native giant wildrye (*Elymus condensatus*) that has stronger seedling vigor than other accessions gives good performance on wet saline and alkali soils.

3. *Legumes for Subhumid Conditions*

The broad objectives and many uses of conservation seedings in the heterogeneous subhumid areas require many legumes. Varieties that have been introduced and adapted or specifically developed for soil conservation have improved the effectiveness of the plantings, particularly for ground cover and soil improvement. The new varieties are hardier, better adapted to specific soil conditions, less susceptible to diseases and insects, or more compatible with the newer grasses.

LADAK is still the most widely used variety of alfalfa under subhumid conditions in the northern intermountain area. Field experience has shown it is better adapted to eroded soils than other varieties. The branching tap root makes it less susceptible to frost heaving, and this may be a factor in survival. The well-known high yield of the first cutting makes the variety ideally suited to the winter-wet and summer-dry climate. Hafenrichter *et al.* (1949) pointed out that cicer milkvetch (*Astragalus cicer*) may supplement alfalfa in conservation seedings at high elevations in the West when frequent frosts occur during the growing season. Field tests indicate that this legume is especially well adapted to soils derived from limestone. DU PUITS alfalfa is coming into use in the northern coastal areas,

where bacterial wilt is uncommon, largely because of superior seedling vigor and yield. In this area alfalfa is limited to deep, well-drained, fertile soils, and lime is often beneficial to establishment and production.

The CASCADE variety of broadleaf birdsfoot trefoil was especially developed for conservation use with AKAROA orchardgrass and ALTA fescue on upland soils subject to erosion in the northern coastal area. Its characteristics were described by Chapin *et al.* (1951). Especially important was the seedling vigor which aided establishment. The GRANGER variety (Wheeler and Hill, 1957) also has seedling vigor but is not quite as winter hardy as CASCADE. Extensive plantings of CASCADE trefoil with orchardgrass have produced excellent yields of high-quality silage and pasture and good ground cover. BEAVER, a hairy variety, and COLUMBIA, a smooth variety of big trefoil (*Lotus uliginosus*), are used on lands that are poorly drained and on tidelands in the same general area.

MONTGOMERY red clover, introduced from New Zealand, in combination with DRUMMOND timothy is superior to other grass-legume combinations for hay production in the northern coastal area. The clover and timothy both reach the hay stage after the late spring rains, and the hay can be cured in rainless early summer weather.

On upland soils in the northern coastal area that are shallow or droughty in summer but require long rotations for soil protection, TALLAROOK subterranean clover (*Trifolium subterraneum*) with one or more grasses has given good erosion control and spring and early summer pasture. The mixture must be carefully grazed and treated with phosphates to maintain ground cover yield (Hafenrichter *et al.*, 1949).

A new legume for the northern coastal area is New Zealand white clover. It is used with grass in general-purpose mixtures, especially on better lowland sites, where it is replacing Ladino and other legumes (Anonymous, 1957a). On such sites slugs often reduce the stands of other clovers in cool, damp weather. The cyanophoric qualities of New Zealand white clover greatly reduce this damage.

4. Semiarid Lands and Range

Large areas of land in the Western region receive less than 15 inches of rainfall, some as little as 5 inches annually. Part of this land is used for the production of cereal grain by the summer-fallow method, but most of it is classed as rangeland. Both water and wind erosion occur on the cultivated lands when the soil is exposed, and erosion is common on rangeland in poor condition. Many acres of land in the semiarid areas were cultivated for grain production during national emergencies and later abandoned, as was shown by Stark *et al.* (1946) and Miller *et al.* (1953). Weedy annual grasses, forbs, and several species of brush have invaded

these abandoned lands. Many acres of abandoned farmland and rangeland in poor condition have been reseeded to grasses. This activity is still progressing steadily (Hafenrichter, 1957).

The cultivated grasses commonly used in agriculture were found to be poorly adapted to land conversion and range reseeding. Crested wheatgrass (*Agropyron desertorum*) was one of the few exotic species available in quantity in the 1930's when this activity was begun. Although widely adapted to semiarid conditions in the Western region, it was limited to the cooler northern portions of the intermountain area. Many new exotic grasses have been tested for this use since 1935 (Short and Woolfolk, 1952; Miller *et al.,* 1953; Allred and Nixon, 1955; Lavin and Springfield, 1955; Hull and Johnson, 1955; Cornelius and Talbot, 1955; Rummel and Holscher, 1955; Plummer *et al.,* 1955; and Anderson *et al.,* 1957). Several selections from ecotypes of native grasses have proved valuable in this work.

Siberian wheatgrass (*Agropyron sibiricum*) has shown more drought resistance, has a longer growing season, and is finer stemmed than crested wheatgrass and is replacing the latter in many parts of the West. WHITMAR wheatgrass, a selection from an ecotype of the native beardless wheatgrass (*A. inerme*), is adapted to the same general area as crested wheatgrass. It is leafier, later, more consistent in production, and retains its nutrients better in the winter months but is somewhat more difficult to establish. TOPAR wheatgrass is a selection from the introduced sod-forming pubescent wheatgrass (*A. trichophorum*). It has good seedling vigor, provides excellent ground cover, remains green into the summer months, and is readily grazed by livestock. It requires slightly more rainfall than the bunch wheatgrasses used in the semiarid areas. TOPAR has a special use in waterways and is one of the better sod-forming grasses for shallow or eroded soils and low fertility sites.

SHERMAN big bluegrass is an ecotype of *Poa ampla,* native to the intermountain area of the Western region. It was described by Hafenrichter *et al.* (1949). It is a vernal dominant bunchgrass that begins growth early in the spring, escapes the drought of the rainless summer, and recovers quickly with early fall rains. It maintains a consistently high level of production under semiarid conditions (Anonymous, 1957a). Stark *et al.* (1950) found that this grass produced higher yields of roots than any of the other drought-tolerant grasses on eroded soils that were depleted of organic matter. Richards and Hawk (1945) showed that it was high in palatability to sheep. Care must be taken to establish SHERMAN big bluegrass because the seeds are small and seedling vigor is weak.

Hardinggrass (*Phalaris t. stenoptera*) has special value for conservation on the annual range of the foothills in the southern coastal area.

Plantings of this grass on selected sites, combined with the use of annual range treated with fertilizers that supply both nitrogen and phosphorus, has extended the grazing season from 6 weeks to 6 months. The details of the method were described by Miller *et al.* (1953), who also determined the best cultural methods for establishing stands of Hardinggrass on these rangelands. Miller *et al.* (1957) found that an early-late system of grazing was superior to others for maintaining the perennial grass and its associated legume, provided the stands were fertilized annually with nitrogen and phosphorus.

BLANDO bromegrass is a variety of the adventive soft chess (*Bromus mollis*) that is widely distributed on the annual range in California. It is used to convert abandoned cropland to range use where perennial grasses are not adapted and for seeding burned-over brushlands. BLANDO brome is a winter-growing, self-seeding annual that was selected for its consistent production of forage and seed, especially under adverse soil and variable climatic conditions. Miller (1955) described its characteristics and cultural requirements. Wimmera ryegrass (*Lolium subulatum*) is used in short rotations with grain under semiarid conditions in the southern part of the coastal area. This self-seeding, early-maturing, winter annual grass can be drilled into grain stubble and provides good ground cover and winter pasture for 1 or 2 years if fertilized. It provides quick but short-lived cover when broadcast on the white ash of brush burns.

Many grasses have been introduced and several native species have been used to reseed desert-grassland ranges in the southern intermountain area. Perennial grasses that lengthen the grazing season and are consistent in production among years under erratic and limiting conditions are superior to adventive annual grasses and invading shrubs. Perennial grasses, when properly managed, would reduce soil erosion, conserve much-needed moisture, and help to stabilize livestock production. Two introduced grasses have proved adaptation to a wide variety of conditions: Lehmann lovegrass (*Eragrostis lehmanniana*) and Boer lovegrass (*E. chloromelas*). Their characteristics are described by Anderson *et al.* (1957). Both grasses are drought resistant. Lehmann lovegrass is easier to establish and has wide adaptation to soil conditions. Boer lovegrass requires slightly more moisture but will tolerate lower winter temperatures. The special cultural practices that have been developed to eliminate competition and conserve moisture to obtain stands of these grasses under very adverse climatic conditions were described by Anderson *et al.* (1957).

Anderson *et al.* (1957) also describe several other exotic and native grasses that may be used for reseeding desert grasslands under special conditions and on more favorable sites. Black grama (*Bouteloua eriopoda*) is one of the best native species for seeding land in low capability classes,

but seed production is still a problem. Arizona cottontop (*Trichachne californica*) survives, produces well, and spreads on low-fertility limey soils with poor moisture-holding capacity once it is established. Seed of this grass is difficult but not impossible to harvest. Wilman lovegrass (*Eragrostis superba*) provides excellent forage, good ground cover, and is easy to establish on sites with deep soil and good moisture. But, this grass cannot be used where minimum temperatures fall below 10–15° F., especially during the establishment year. Turkestan bluestem (*Andropogon ischaemum*) spreads naturally after a rather long establishment period, but it requires sites with good soil and moisture such as are found in swales. Local ecotypes of sideoats grama (*B. curtipendula*) have wide adaptation to soils in the upper limits of the desert grassland where rainfall is adequate. Good seedbeds are required for establishment. Sand dropseed (*Sporobolus cryptandrus*) is used on well-drained sandy soils for ground cover and for spring and early summer grazing. Established stands are persistent and drought resistant.

Few legumes have been found that produce reliable stands and yields or contribute directly or through the grasses in mixtures to conservation or forage production on semiarid or range lands. Alfalfa is the most reliable legume on better sites in the intermountain area. LADAK is the best variety available on the market in the north, and COMMON or one of the nonhardy varieties in the south. Recently developed "pasture-type" alfalfas such as NOMAD and RAMBLER (Wheeler and Hill, 1957) may prove to be even better for grazing use than LADAK. The winter annual self-seeding rose, DIXIE crimson, and MT. BARKER subterranean clovers are used on specific sites for reseeding the annual ranges in the southern coastal area. Love and Sumner (1952) describe the recently introduced rose clover (*Trifolium hirtum*) and recommend that it be mixed with subterranean and crimson clover when seeding on the annual range. Hafenrichter (1956) pointed out that the pH of the soil may affect the relative performance of these three clovers in such seedings.

A new winter annual reseeding legume, LANA vetch, has just been released by the Soil Conservation Service and the California Agricultural Experiment Station for use in range reseeding in California. It is a selection from woollypod vetch (*Vicia dasycarpa*). Field tests show that LANA vetch is unusually consistent in production among years, is easy to establish, matures early, and reseeds consistently when moderately grazed. Improvement of the annual range is the primary use of LANA vetch, and it is adapted to a wide range of soil and rainfall conditions. It is palatable to livestock, both when green and when dry, and this is a valuable adjunct on annual range. Good stands can be established by drilling seed of this legume directly into the litter of the annual forage range, and stands have

been obtained by broadcasting seed on sites having adequate residue or on the white ash of brush burns. The variety was described by Miller (1958). LANA vetch shows promise for use as a self-seeding winter cover crop.

C. GRASSES AND LEGUMES FOR SPECIAL CONSERVATION USE

McLaughlin and Brown (1942) described the extensive coastal sand dunes along the ocean in the Western region. They explained the reasons for accelerated erosion and detailed the control measures. Vegetation was by far the most effective method of stabilization. The work was done in two steps. The sand was first stilled with plantings of European beachgrass (*Ammophila arenaria*), American beachgrass (*A. breviligulata*), or American dunegrass (*Elymus mollis*). Special strains with high survival and ability to tiller rapidly were developed. These grasses vary in their response to temperature at the time of transplanting and to fertilizers, as was shown by Brown and Hafenrichter (1948). A secondary planting of perennial grasses and legumes is made for permanent stabilization after sand movement is stopped with beachgrass or dunegrass. The most effective grasses were CLATSOP red fescue (*Festuca rubra*) and ALTA fescue. These were planted with purple beachpea (*Lathyrus maritimus*) on upland sites and with birdsfoot trefoil where the water table was high (Brown, 1948).

VOLGA wildrye is a variety of *Elymus giganteus* used for the stabilization of active sand dunes in the northern part of the intermountain zone where annual precipitation is 10 inches or more. Smith *et al.* (1947) described this sod-forming grass and showed that it provided both initial and permanent stabilization of inland sand dunes. It was not highly palatable to livestock or rabbits, which often destroy the effectiveness of grass plantings by heavy grazing and trampling. It is not adapted for use on coastal dunes.

SODAR wheatgrass, a selected strain of the native streambank wheatgrass (*Agropyron riparium*) is used for stabilizing irrigation canal banks, road cuts and fills, and airport surfaces under semiarid conditions in the northern part of the intermountain area (Douglas and Ensign, 1954). This grass is easy to establish, spreads by rhizomes, and makes a smooth low-growing sod for control of wind and water erosion.

Hard fescue (*Festuca duriuscula*) is an introduced grass similar to the native Idaho fescue (*F. idahoensis*) but produces good yields of seed and is easy to grow under subhumid conditions in the northern intermountain area. It is especially useful in alfalfa-grass mixtures for soil improvement, and Woods *et al.* (1953) showed that it produced more

fine fibrous roots than any other grass in a 5-year test. It is also used for stabilizing road cuts and fills and pond embankments.

Kikuyugrass (*Pennisetum clandestinum*) is especially well adapted to the stabilization of waterways in the warm southern Pacific coast area. Cuttings are used for planting, and fertilizers are required to maintain growth and vigor. In some localities Kikuyu has been regarded as weedy, but no other plant has been found to equal it in value for waterways that have a high discharge rate, and experience shows that it is easy to control. Napiergrass (*P. purpureum*), a warm-weather grass, sometimes serves the dual purpose of a field windbreak and forage. It requires good soil and moisture and warm weather for maximum growth and production.

CUCAMONGA bromegrass, a domesticated variety of *Bromus carinatus*, is a self-seeding winter cover crop especially developed for use in vineyards on sandy soils subject to wind erosion in the southern part of the Pacific coast area. The characteristics of this variety and the management required to control erosion and perpetuate the stand were described by Lemmon *et al.* (1950). They are quick recovery after fall rains, rapid growth during the winter, early maturity in the spring, high yields of seed, and some shattering of ripe seed before the stand is reduced with subsurface tillage to provide a mulch.

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THE ROLE OF SULFUR IN SOIL FERTILITY

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I. Introduction

Sulfur has been described as a neglected plant nutrient. Its essential nature was demonstrated more than a century and a half ago and yet this nutrient has received only sporadic study by agronomists.

In surface soils sulfur is predominantly in the organic fraction, and native supplies of sulfur vary with supplies of organic matter, from low to adequate. This native sulfur is supplemented by variable additions from rainwater, irrigation water, atmosphere, fertilizers, insecticides, and fungicides. Although sulfur deficiency under field conditions is not universally a problem, it may be acute in some areas. This probably accounts for the neglect of sulfur nutrition as a general problem for research.

Sulfur is also essential in animal nutrition. A complete assessment of sulfur nutrition thus involves soil, plant, and animal phases, and the interrelationships of all three.

This paper reviews the role of sulfur in plant metabolism, the relation of adequately and undernourished forages to animal well-being, and the requirements of agricultural crops for sulfur. Supplies of sulfur from soils and extraneous sources are balanced against these requirements, and areas of known and potential sulfur deficiency delineated. It is pointed out that recent trends in technology may alter the present balance between requirements and supplies.

II. Role of Sulfur in Plant Metabolism

Sulfur is a constituent of a number of plant compounds Most important of these are the plant proteins so valuable in animal nutrition.

The interactions of sulfur and certain other nutrients have important relations to the quality and nutritive value of some crops. Interactions of sulfur and phosphorus and sulfur and nitrogen have been studied particularly.

A. Sulfur Compounds in Plants

Sulfur is a constituent of methionine and cystine, two amino acids commonly found in plants. Methionine is essential in animal nutrition. Cystine, although not essential, may complement methionine when the latter is present in suboptimal amounts. Methionine contains 21 per cent and cystine 27 per cent sulfur.

Two growth regulators, thiamine and biotin, contain sulfur. The characteristic odors and flavors of certain vegetables are due to volatile compounds of sulfur, as the mustard oil glycosides. Sulfur occurs in glutathione, which is important in oxidation-reduction reactions. Sulfur in compounds other than the amino acids generally constitutes only a small proportion of the total.

Sulfur is not a constituent of chlorophyll, nevertheless sulfur-deficient plants are chlorotic. Ergle (1953) reported a reduction of 40 per cent in chlorophyl content of sulfur-deficient cotton plants as compared with controls.

Ergle and Eaton (1951) summarized biochemical data relating to the effect of sulfur on cotton, *Gossypium hirsutum;* tomato, *Lycopersicon esculentum* Mill; soybean, *Glycine max;* sunflower, *Helianthus annuus* L.; and mustard, *Brassica nigra.* There were notable differences, but also some common features, in reactions of the five plants. In general, sulfur deficiency caused higher concentrations of soluble nitrogen in all tissues of all plants. Effects on protein were not consistent. Sugars were reduced in the stems of sulfur-deficient cotton, soybean, and sunflower, but increased in tomato and mustard. Starch and hemicellulose were usually increased or unchanged.

Needham and Hauge (1952) found sulfur additions to increase the amounts of six of the B vitamins in alfalfa, *Medicago sativa.* Fox (1956) studied the relation of sulfur to the vitamin A content of alfalfa. Phosphorus alone produced alfalfa hay with 156,000 units of vitamin A per pound, sulfur alone produced hay with 175,000 units, whereas combined application of phosphorus and sulfur raised the level to 196,000 units.

B. The Sulfur-Nitrogen Balance and Its Significance in Animal Nutrition

The nutritive value of plants as feed is associated with their protein content. The two sulfur-bearing amino acids are thus of particular importance as they enter into the synthesis of plant proteins.

Nonruminant animals are entirely dependent on amino acids already synthesized. Although synthetic methionine is available for supplemental feeding, the principal and most widely utilized source of this amino acid is plant protein.

The situation is different for ruminants since part of their amino acid requirement is satisfied by bacterial synthesis during digestion from simple forms of nitrogen and sulfur. However, even for ruminants nitrogen and sulfur must be offered in suitable amounts and proportions.

1. *Sulfur-Nitrogen Ratios*

Bardsley and Jordan (1957) found that sulfur-deficient white clover, *Trifolium repens* L., growing on seven representative southeastern soils had S:N ratios ranging from 1:20 to 1:30, with a mean of 1:24. Where sulfur was supplied, the S:N ratios ranged from 1:10 to 1:17, with a mean of 1:14. These data illustrate the variation in the proportions of sulfur and nitrogen occurring in plants.

Loosli (1952) noted that feeds having S:N ratios wider than 1:15 might be assumed to be deficient in sulfur for ruminants, whereas those having ratios narrower than 1:15 may have a surplus of sulfur. Thus the sulfur-deficient clover grown by Bardsley and Jordan would be inferior as feed, even for ruminants.

2. *Amino Acid Synthesis*

The sulfur-bearing amino acids, methionine and cystine, are found in all plants. The relation of sulfur supply to the synthesis of these amino acids has been studied both from a quantitative standpoint and as it affects the quality of the protein formed therefrom.

Methionine and cystine have been increased in alfalfa, clover, soybeans, and sudan grass, *Sorghum vulgare* var. SUDANESE, by sulfur additions (Tisdale *et al.*, 1950; Sheldon *et al.*, 1951; Bardsley and Jordan, 1957). Representative data are reproduced in Table I.

TABLE I

Effect of Sulfate Ion Concentration in the Nutrient Solution on the Methionine, Cystine, Total Sulfur, and Total Nitrogen Content of Alfalfa (C-10)[a]

Sulfate ion concentration (ppm)	Methionine (%)	Cystine (%)	Sulfur (%)	Nitrogen (%)
0	0.153	0.170	0.129	3.66
1	0.151	0.170	0.141	3.74
3	0.157	0.176	0.153	3.50
9	0.167	0.212	0.192	3.52
27	0.187	0.225	0.224	3.50
81	0.173	0.220	0.229	3.50

[a] From Tisdale *et al.* (1950), harvest of November, 1947.

The lower percentages of methionine and cystine in dry matter of sulfur-deficient forages have important implications from a nutritional standpoint. A higher feed intake of the sulfur-deficient as compared with the

sulfur-fertilized forage may be necessary to assure adequate dietary levels of these amino acids, particularly for nonruminants.

Perhaps more important from a nutritional standpoint is the effect of sulfur additions on the concentration of methionine and cystine in the plant protein, which reflects the quality of the protein.

Tisdale *et al.* (1950) found the concentrations of methionine and cystine per gram of nitrogen to increase with increasing concentrations of sulfur supplied to alfalfa growing in sand cultures. Despite this increase, the highest methionine contents fell short of that of whole egg protein, which was used as a standard of comparison.

Renner *et al.* (1953) found that sulfur-containing fertilizers increased the level of methionine in the protein of wheat, *Triticum vulgare,* grown in a five-year rotation of three years' grain followed by two years' mixed legume hay. The level of methionine was not affected in continuous wheat (wheat-fallow). Similarly, sulfur-containing fertilizers increased the level of methionine in the protein of first year barley, *Hordeum vulgare,* and, less consistently, in the protein of third-year barley.

Rendig (1956), on the other hand, found that the protein of alfalfa was not enriched in methionine by sulfur applications. Bardsley and Jordan (1957) reached a similar conclusion in a study with white clover, although cystine in the protein was increased by sulfur additions. In the latter study it was observed that the quality of the protein in terms of methionine was comparable to that of cottonseed and soybean meal, and superior to that of the peanut.

This conflicting evidence suggests that further study is needed to establish the relation of sulfur supply to the quality of plant proteins. Insofar as the quality of protein is improved, the nutritive value of the feed is correspondingly enhanced.

C. Formative Effects and Sulfur Deficiency Symptoms

The most striking feature of sulfur-deficient plants is the stunted chlorotic growth.

Stems of sulfur-deficient plants are shorter and thinner than normal, and they are inclined to be woody (Ergle and Eaton, 1951). Leaf area is much reduced. Accompanying the general depressed growth, a deficiency of sulfur reduces fruiting. Ergle and Eaton (1951) grew cotton at five levels of sulfate supply ranging from 0.1 to 200 ppm. At 65 days of age there were 0.5, 3.2, 14.8, 23.4, and 22.5 developing bolls per plant.

Chlorosis may involve the whole plant or it may be severe only on the younger leaves. Plants resemble those which are deficient in nitrogen, except that they do not develop characteristic leaf patterns, as is usual with

nitrogen deficiency. In cases of extreme sulfur deficiency cotton plants may die in the seedling stage. Field response of cotton to sulfur in an experiment at Brewton, Alabama, is shown in Fig. 1.

Anthocyanin pigmentation develops in some plants with severe sulfur deficiency. Hilder and Spencer (1954) noted that sulfur-deficient medics, *Medicago denticulata* and *M. orbicularis,* developed purple and brown tints and were not notably light green. Typical chlorosis appeared when a small amount of sulfur was added and the plants grew a little.

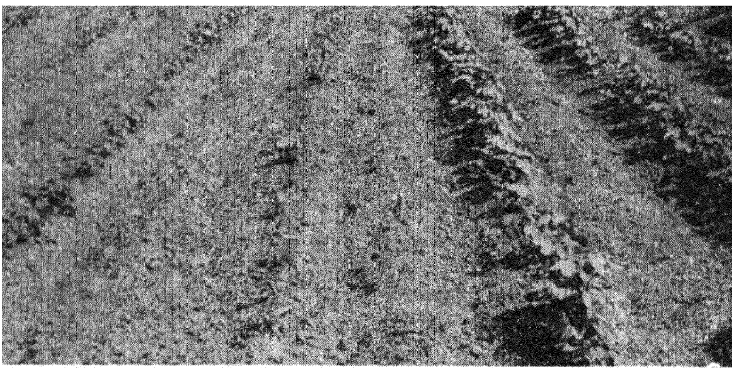

FIG. 1. Response of cotton to sulfate in early growth stages on Kalmia fine sandy loam near Brewton, Alabama. Plot at left received sulfur-free fertilizer whereas one at right received similar fertilizer containing sulfate.

Sulfur has been reported to increase root systems of plants, but in many cases this observation was made without reference to the plant as a whole. Anderson and Spencer (1950) reported that roots comprised a lower proportion of total plant weight where sulfur was added to the culture medium. K. Spencer (unpublished data, Mississippi State College, 1956) found roots of white clover to range between 27 and 42 per cent of total plant weight. The higher figure was obtained with no sulfur (except impurities) in sand culture; the lower figure with 200 ppm sulfur. Although sulfur applications may stimulate root growth, the proportion of roots to tops may actually be reduced because of a relatively greater growth of tops.

Sulfur deficiency has been shown to decrease numbers and weights of nodules on legumes (Duley, 1916; Miller, 1921; Anderson and Spencer, 1950). Anderson and Spencer consider this a reflection of reduced growth and consequent reduced demand for nitrogen by the host plant.

III. Crop Requirements for Sulfur

Total sulfur in plants may approach or even exceed the concentration of phosphorus (Beeson, 1941). The ratio of $N:P_2O_5:K_2O:SO_3$, as calculated for all crops harvested in the United States, is of the order 1.0:0.4: 0.6:0.3 (Mehring and Bennett, 1950). Thus, although sulfur is not considered a primary nutrient, its importance to crops approaches those of the primary group.

A. Amounts Required by Crops

Amounts of sulfur absorbed by some representative crops are given in Table II. These amounts vary with the kind of crop and the amount available from soil or other sources. Accordingly the values in Table II are approximate, and are given as ranges rather than as absolute amounts.

TABLE II

Sulfur Absorbed by Crops

Crop	Acre yield	Sulfur absorbed (lb. per acre)
Cabbage, *Brassica oleracea*	15 tons	19–38
Turnips, *Brassica rapa*	20 tons	25–35
Onions, *Allium cepa*	15 tons	18–20
Clovers, *Trifolium* spp.	4 tons	15–20
Alfalfa, *Medicago sativa*	5 tons	20–24
Cotton, *Gossypium hirsutum*	1.5 bales	12–15
Corn, *Zea mays*	100 bushels	8–10
Grasses, *Gramineae* spp.	4 tons	8–10
Wheat, *Triticum vulgare*	40 bushels	9–12

1. *Kind of Crop*

Some vegetable crops as cabbage, turnips, and onions, absorb particularly large amounts of sulfur. These crops have relatively short growth periods; hence, a supply of readily available sulfur is especially important.

Legumes fall in an intermediate group. The requirements of cotton for sulfur are comparable to those of certain leguminous crops.

Corn, grasses, and small grains have lower requirements than crops in the two groups above, particularly when grown at moderate nitrogen lev-

els. Nelson (1956) observed that no instances have been reported in the United States where field applications of sulfur resulted in increased growth of corn. Grasses in Australia (Andrew *et al.*, 1952), wheat in Washington (Reisenauer and Leggett, 1957), and both cereals and grasses in Alberta (Alberta Advisory Fertilizer Committee, 1956) have been found only moderately responsive to applications of sulfur at low nitrogen levels, but very responsive when these nutrients were added in combination. Responses to sulfur have been observed in the Southeast with Coastal Bermuda grass, *Cynodon dactylon*, liberally fertilized with nitrogen. Grass crops not liberally fertilized with nitrogen failed to show a need for sulfur (Jordan and Bardsley, 1958).

2. *Amounts Available to Crop*

Most crops absorb sulfur readily as increasing amounts are applied with fertilizer. Representative data from field experiments are given in Table III. Sulfur percentages in Table III range from a deficient level to

TABLE III

Sulfur Percentages in Crops as Affected by Sulfur Applied with Fertilizers[a]

Sulfur applied (lb. per acre)	Per cent sulfur in crops: Cotton	Clover	Tobacco	Coastal bermuda grass[b]
0	0.17	0.16	0.11	0.11
4	0.18	0.17	0.15	0.11
8	0.21	0.18	0.11	0.15
16	0.22	0.20	0.15	0.19
32	0.27	0.21	0.18	0.21

[a] Data from Jordan and Bardsley (1958).
[b] With liberal nitrogen fertilization.

those more than adequate. This is evident since crops on the no-sulfur treatment were reduced in yield, and there were no further yield increases for applications above the 8-lb. rate.

In leguminous crops much of the increase in total sulfur is synthesized into protein sulfur (Andrew *et al.*, 1952; Needham and Hauge, 1952). In nonlegumes, sulfates may increase considerably with increased sulfur additions (Andrew *et al.*, 1952; Ergle and Eaton, 1951). If nonlegumes are well supplied with nitrogen, however, protein formation may proceed as in legumes (Anderson and Spencer, 1950).

Minimum levels of plant sulfur for adequate nutrition have been tentatively established for several species. For alfalfa (Goodall and Gregory, 1947) and cotton leaves and petioles at midseason (Jordan and Bardsley, 1958), critical values have been given as 0.2 per cent. An approximately equivalent value is indicated for sugar beets, *Beta vulgaris* L. (Ulrich, 1956). For field-grown clover, a range from 0.10 to 0.16 per cent is reported (Jordan and Bardsley, 1958).

B. Uptake and Translocation of Sulfur

Sulfur is absorbed from the soil principally as the sulfate ion. It has also been demonstrated that plants may absorb sulfur dioxide through their leaves (Fried, 1948; Thomas *et al.*, 1950).

Sulfates may accumulate within the plant as a reserve or they may be metabolized into amino acids, plant hormones, or other organic sulfur compounds. Nightingale *et al.* (1932) found that organic sulfur compounds once synthesized by tomato plants may subsequently undergo proteolysis, translocation, and re-use in meristematic tissue. However, Ergle (1954) found no evidence of such withdrawal, translocation, and re-use of sulfur in his studies with cotton.

IV. Sources of Sulfur for Plants

Although sulfur has many properties in common with phosphorus as a plant nutrient, the problem of sulfur economy in soils differs from that of phosphorus. The atmosphere contains variable amounts of sulfur gases that may be added to the soil through precipitation and through adsorption by the soil. Also, plants can take up sulfur gases through stomatal openings. The sulfur problem is further complicated by the fact that many fertilizer materials contain sulfate as an incidental component. These and other sources of sulfur will be discussed in this section. Plants often obtain sulfur from more than one source.

A. Sulfur in Soils

The lithosphere contains about 0.06 per cent sulfur. During the process of weathering much of the sulfur in pyrites and other metallic sulfides is transformed to sulfate and either accumulates or is lost by leaching.

1. Total Sulfur

Only limited data are available on the sulfur constituents in soils. Determinations have usually been limited to total sulfur and sulfate. Undoubtedly many organic and inorganic compounds may occur in soil to some extent.

The total sulfur content of soils is variable. Robinson (1917) reported

total sulfur content for a number of soils. His data show a range of 0.008 to 0.136 per cent sulfur for the top soil. In most cases the subsoils contained about the same amount of sulfur. Byers *et al.* (1938) gave 0.045 per cent as the average content of the A and B horizons of 18 representative soils.

Evans and Rost (1945) determined the amount of organic sulfur in a number of Minnesota soils. Their data show that the chernozems, black prairie soils, northeastern podsols, and northcentral podsols contained 73.3, 71, 49.5, and 45.4 per cent, respectively, of their total sulfur in the organic form. In the subsurface layers studied they found that only 15.9 per cent was in the organic form. Evans and Rost show a direct relationship between the organic sulfur content of surface soils and nitrogen and carbon. This would be expected if most of the sulfur is in the organic form.

Organic sulfur in soils is an important reserve supply of the element for plant growth. As organic matter is decomposed, the sulfur is released mainly as sulfate, which is the principal source of sulfur for higher plants. The transformations of sulfur in soils by microorganisms are discussed in detail by Starkey (1950).

Fallowing accelerates the decomposition of soil organic matter, and has been shown to temporarily increase available sulfur and plant growth on sulfur-deficient soils (Commonwealth Scientific and Industrial Research Organization, 1954). Hilder and Spencer (1954) report outstanding response to sulfur top-dressed on the otherwise undisturbed surface of a pasture. The same soil excavated and placed in greenhouse pots failed to show similar response. The difference is attributed to disturbance and aeration of the soil, a procedure which in some respects resembles fallowing.

2. *Sulfates and Factors Affecting Their Adsorption*

In well-aerated soils most of the inorganic sulfur is in the sulfate form. Sulfates added or released in the soil by microbial decomposition are subject to loss by leaching. Lysimeter studies reported by Lyon and Bizzell (1918) show that the removal in drainage water was 3 to 6 times as much as was removed by crops.

Factors affecting the loss of sulfur by leaching have received only slight attention. Mattson (1927) demonstrated that sulfate was adsorbed by some soil colloids and that the adsorption capacity of a Norfolk soil colloid increased with increasing acidity. Lichtenwalner *et al.* (1923) determined the adsorption capacity of iron and aluminum hydrogels and found that they would adsorb sulfate. Ensminger (1954) determined the sulfate content and adsorption capacity of 12 Alabama soils. His results are presented in Table IV. No acetate-extractable sulfate was found in the A

TABLE IV

Sulfate Content and Sulfate Adsorption by Horizons of 12 Alabama Soils[a]

Soil type	Sulfate-sulfur extracted by sodium acetate pH 4.8 ppm S in soil			Sulfate-sulfur adsorbed from $CaSO_4$ solution containing 10 ppm S ppm S in soil			Calculated adsorption capacity—sum of soluble sulfate plus adsorbed sulfate ppm S in soil		
	A	B	C	A	B	C	A	B	C
Oktibbeha clay	0	25	1	0	16	5	0	41	6
Houston clay	0	1	0	0	16	26	0	17	26
Eutaw clay	0	0	0	16	84	132	16	84	132
Susquehanna fine sandy loam	0	0	0	0	174	142	0	174	142
Decatur silty clay loam	0	134	0	32	105	174	32	239	174
Cecil sandy loam	0	151	190	0	110	221	0	261	411
Davidson sandy clay loam	0	68	43	42	163	216	42	231	259
Ruston sandy loam	0	0	66	10	47	174	10	47	240
Orangeburg sandy loam	0	0	36	10	68	174	10	68	210
Norfolk sandy loam	0	80	149	0	32	68	0	112	217
Greenville fine sandy loam	0	0	18	21	42	68	21	42	86
Hartsells fine sandy loam	0	---	-	0	42	52	0	---	

[a] Data from Ensminger (1954)

horizon of any of the soils. Some of the soils contained appreciable quantities of sulfate in the B and C horizons. The B and C horizons of most of the soils showed a capacity to adsorb sulfate. Ensminger (1954) also determined the sulfate adsorption capacity of a number of materials including clay minerals and a soil colloid. His data showed that aluminum oxide had a high adsorptive capacity for sulfate.

Overstreet and Dean (1951) postulated that the mechanisms by which chloride, sulfate, and phosphate ions are held in an acid soil are similar. Barbier and Chabannes (1944) concluded from their studies that sulfate ions were more strongly adsorbed than chloride ions but less strongly than phosphate.

Kamprath *et al.* (1956) studied the effect of pH on adsorption of sulfate by three soils. Adsorption data for Norfolk soil at various solution concentrations of sulfate are presented in Fig. 2. The data show that sulfate adsorption decreased with increasing pH at all concentration levels. These data indicate that very little sulfate would be held by a surface soil limed to pH 6.0 or higher. Results reported by Ensminger (1954) show that lime reduced the amount of extractable sulfate in the 6–12 inch layer of a Eutaw clay. Lysimeter studies by MacIntire *et al.* (1945) show that liming increased the outgo of sulfate.

Other factors affecting the retention of sulfate have been reported. Ensminger (1954) found that superphosphate reduced the amount of

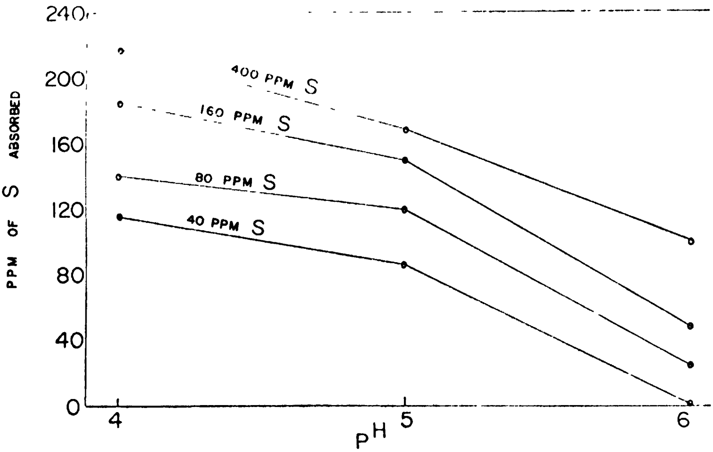

FIG. 2. Effect of pH on the adsorption of sulfate by a Cecil soil at various solution concentrations of sulfate. From Kamprath *et al.* (1956).

sulfate retained in the surface 6 inches of a Cecil sandy clay loam. He also found that dilute phosphate solutions were effective in extracting sulfate from soils. Kamprath *et al.* (1956) showed that under laboratory conditions phosphate was effective in reducing sulfate adsorption. This means that well-phosphated soils would not be likely to retain much sulfate in the surface layers. However, since phosphate does not move downward to any appreciable extent, subsurface layers should not be affected.

B. SULFUR IN RAIN AND IRRIGATION WATER

Numerous studies have been made to determine the amount of sulfur brought down in rainwater. Some of the earlier studies may have recorded high values because rainwater was collected in corrodible metal containers. Alway *et al.* (1937) noted that such metals react with sulfur gases in the atmosphere and that the reaction products are washed into the collecting vessel and determined as sulfate. He found errors ranging up to six-fold from rainwater collectors of this type.

Much of the data on sulfur brought down in rainwater was summarized by Eriksson (1952). His summary shows that yearly amounts of sulfur brought down vary a great deal with location, due to differences in atmospheric pollution. Eriksson mentions the following sources of sulfur in the atmosphere; combustion of coal and other materials, decomposition of organic matter, and spray from the sea. In general, the figures from the United States were higher than figures from Europe.

In some cases seasonal trends in the quantity of sulfur brought down have been noted. Leland (1952) found that sulfur in rainwater at Ithaca, New York, averaged 37.63 lb. per acre for the 6 months from November to April and 11.23 lb. for the 6 months from May to October. Johnson (1924) measured sulfur in rainwater by quarters at 7 locations in Kentucky and found the highest values for the winter months. Both workers attributed the high values of the winter months to consumption of coal for home heating.

Wilson (1926) reported annual additions of sulfur from rainwater at Ithaca, New York, ranged from 25 to 36 lb. per acre per year during the period from May, 1918 to May, 1923. A coal-burning heating plant was put in operation near the collection point in the fall of 1923. Thereafter sulfur accretions ranged from 46 to 65 lb. per acre annually. Data presented by Jordan *et al.* (1957) show that the operation of a steam plant near Tuscumbia, Alabama, increased the sulfur added in rainwater from about 5 lb. per acre per year to about 10 lb. Based on an average sulfur content of the coal burned in 1956, it is estimated that 89,000 tons of sulfur was given off by the steam plant. Evidently the stacks were high enough to cause the distribution of the effluents over a wide area. The data from Ithaca, New York, and Tuscumbia, Alabama, reflect the influence of combustion gases as a source of sulfur in the United States.

Recent data reported by Jordan *et al.* (1957) show the amount of sulfur brought down in rainwater at 108 locations in the southeastern United States. Rainwater from Virginia, Kentucky, and Tennessee contained more sulfur than from the states farther south. In the southern tier of states a few locations gave high sulfur values because of proximity to industry. In rural areas of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas mean accretions of sulfur in rainwater were 5.8, [illegible], and 6.3 lb. per acre in 1953, 1954, and 1955, respectively. This would make only a minor contribution to the sulfur needs of crops in these states.

In the West, sulfur added in irrigation water may be enough to supply total crop requirements. Thorne and Peterson (1954) summarized the data on chemical composition of water samples from nineteen rivers used for irrigation in western United States. The sulfur content of the water ranged from about 3 to 1,849 lb. per acre foot of water. The majority of the waters contained more than 40 lb. of sulfur per acre foot.

Well water used for irrigation may also contain a considerable amount of sulfate. Data reported by Jensen *et al.* (1951) show that well water used for irrigation in Idaho ranged from about 25 lb. sulfur per acre foot to 700 lb.

C. Atmospheric Sulphur

Surface soils and plants may take up atmospheric sulfur. Thus, the concentration of sulfur in the atmosphere may be directly related to the sulfur nutrition of plants. Most of the atmospheric sulfur is in the form of SO_2.

Alway *et al.* (1937) concluded that sulfur adsorbed by the soil made an important contribution to plants but that the amount would be likely to be less than from sulfur in rainwater. Alway used lead peroxide cylinders and soils exposed in petri dishes to determine the adsorption of atmospheric sulfur. Using two soils for twenty periods, he found that the soils adsorbed only 22 per cent as much sulfur on the average as lead peroxide cylinders of the same area. Jordan *et al.* (1957) reported results from Alabama and Virginia showing the adsorption of sulfur gases by lead peroxide cylinders. The eight locations in the vicinity of Tuscumbia, Alabama, ranged from 5.6 to 27 mg. per 100 $cm.^2$ per year. The 16 locations in Virginia ranged from 10.7 to 54.8 mg. of sulfur per 100 $cm.^2$ per year. If exposed soil is only 22 per cent as effective as an equal surface of lead peroxide, the Alabama soils would adsorb less than 5.5 lb. of sulfur per acre per year and the Virginia soils less than about 11 lb.

Work by Thomas and Hendricks (1943) indicated that SO_2 can be adsorbed through the leaves of plants. Since the root medium was not isolated from the atmosphere there was a possibility that SO_2 was adsorbed by the root medium and after oxidation to sulfate taken up by the plant. Fried (1948) used S^{35} to demonstrate the adsorption of SO_2 directly through the leaves.

D. Sulfur in Fertilizers

The incidental addition of sulfur in fertilizers has been and will continue to be an important source of sulfur for crop production. Mehring and Bennett (1950) summarized the data showing the sulfur content of fertilizers, manures, and soil amendments. Normal superphosphate contains an average of about 12 per cent sulfur. Since superphosphate is the source of phosphorus in many mixed fertilizers, most mixed fertilizers contain a considerable content of sulfur as sulfate. According to Mehring and Bennett, the average sulfur content of mixed fertilizers consumed for the year ending June 30, 1948 was 7.74 per cent. This means that most fertilizers would supply enough sulfur to meet the requirements of most crops. The present trend is toward the use of higher analysis fertilizers, which will be likely to contain less sulfur.

E. Sulfur in Insecticides and Fungicides

Elemental sulfur is often added to the soil in insecticides and fungicides. Sulfur added in this manner for disease control with peanuts may amount to 50 or 60 lb. per acre. Under favorable conditions in the soil, elemental sulfur is oxidized to sulfate by microorganisms. It is unlikely that the sulfur would be oxidized in time to benefit the immediate crop but the succeeding crops may be benefited by residual sulfate.

It is possible that elemental sulfur may enter into the nutrition of some plants by being absorbed directly through the leaves. Turrell and Weber (1955) used radioactive elemental sulfur to show that it can be absorbed through the leaves of the lemon plant.

V. Removal of Sulfur from Soils

There are continual losses which tend to offset the additions of sulfur to the soil-plant system. Plant removal, leaching beyond the root zone, and erosion are the principal ways in which sulfur is lost from soils.

A. Plant Removal

In early methods of analysis considerable error resulted from volatilization of sulfur during ashing, and the requirements of crops for this nutrient were greatly underestimated. Hart and Peterson (1911) were first to call attention to the appreciable amounts now known to be removed by crops (Table II; Section III, A). Sulfur contained in the marketed portion of a crop is lost to the soil. In other systems of farming the sulfur may be partially or almost completely returned to the soil in crop residues and animal by-products.

Within recent years there have been remarkable advances in soil management and crop-production techniques which have resulted in increased yields of all major crops. Further advances are in prospect. As yields are increased so are the demands for sulfur, and plant removals are likely to increase rather than diminish.

B. Leaching

Some early lysimeter studies showed very large losses of sulfur by leaching. In Illinois, measured losses ranged from 35 to 55 lb. of sulfur per acre annually (Illinois Agricultural Experiment Station, 1937). The low loss was from a plot in continuous alfalfa, the high loss from continuously bare soil. In New York, losses from a Dunkirk silty clay loam amounted to about 43 lb per acre annually (Lyon and Bizzell, 1936). These measure-

ments were made in lysimeters which did not permit runoff, and water not utilized in evapotranspiration of necessity leached through the soil profile. Measurements of sulfur losses by such technique are probably overestimations.

Data from lysimeters permitting runoff are more applicable to sloping upland soils. In one such study the losses from eight Illinois soil types maintained in fallow ranged from 1.5 to 57 lb. per acre annually, with a mean of 30 lb. (Stauffer and Rust, 1954). In Wisconsin, annual losses from a Fayette silt loam with 10 per cent slope were approximately 1 lb. per acre when crops were grown and 3 lb. per acre from uncropped soil (Kilmer *et al.*, 1944).

In these studies losses of sulfur by leaching were high in soils well supplied with native sulfur or where sulfur additions were made in fertilizer. Losses were much more moderate where native supplies and accretions were lower. This suggests caution against any general application of the higher sulfur losses quoted above. In common with some other nutrients, removal of sulfur by leaching is less from cropped than from uncropped soils.

As noted in Section IV, A, 2, additions of lime and phosphate to the soil accelerate the leaching of sulfur.

C. Erosion

Cultivated soils continually suffer some loss of sulfur by erosion. Since an important part of the soil reserves of sulfur is in the organic fraction which is most abundant in surface soils, the potential for loss is considerable. Too, sulfur additions from extraneous sources are made to surface soils.

As was noted with leaching losses, soils well supplied with native sulfur and those which receive large extraneous additions suffer the greatest losses. Losses are more moderate where native supplies and accretions are lower. Lipman and Conybeare (1936) estimated that as an average for the United States, about 6 lb. of sulfur per acre are lost each year in this manner. McHargue and Peters (1921) estimated that the Ohio River carried away sulfur in solution equivalent to 35 lb. per acre annually from the entire drainage basin.

D. Microbial Transformations

Transformations of both organic and inorganic sulfur compounds within the soil are largely microbial. They are accomplished by diverse organisms. Under aerobic conditions, sulfur is completely oxidized to the sulfate form. Since in humid soils most of the reserve sulfur is in the organic fraction, microbial transformation is essential before the sulfur is

usable by plants. The same transformation renders sulfur susceptible to loss by leaching, as discussed in Section V, B.

Under anaerobic conditions, reduced forms such as sulfides predominate. This is of importance only in water-logged soils, along seacoasts, and in similar situations. Under these specialized conditions some losses of sulfur may result through volatilization as hydrogen sulfide.

VI. The Sulfur Cycle

From the foregoing discussion of gains and losses of sulfur, it is evident that this nutrient is involved in an endless and recurrent cycle. Initially derived from soil minerals, sulfur is also added to the soil by rain and

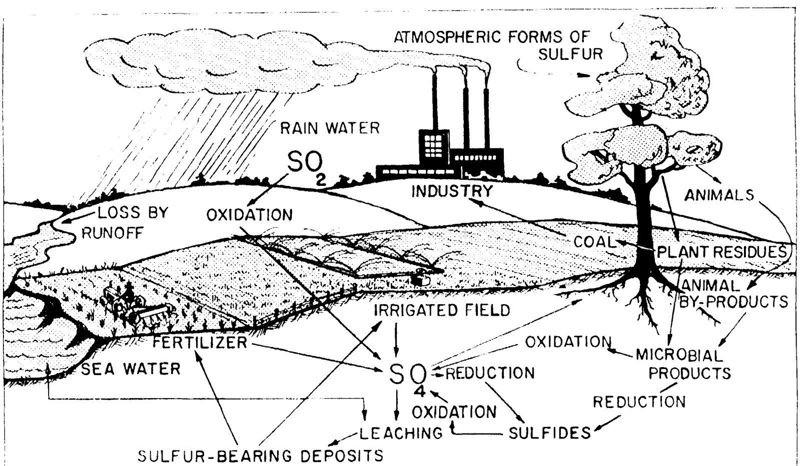

FIG. 3. Diagrammatic representation of the sulfur cycle.

irrigation water, atmosphere, fertilizers, insecticides, and fungicides. It is removed from the soil by plants and partially or completely returned to it in plant residues and animal by-products. Thence the organic sulfur undergoes decomposition to a form in which it is again usable by plants.

Some sulfur is lost to the soil-plant system by runoff and leaching, and accumulates in sea water and deep sulfur-bearing deposits. This accumulated sulfur again enters surface reactions in sea spray or through mining of coal, sulfur-bearing ores, and elemental sulfur.

A diagrammatic representation of the sulfur cycle is presented in Fig. 3.

VII. Crop Responses to Applied Sulfur

In those areas where crop requirements for sulfur exceed available supplies, economic increases in crop yields have followed additions of sulfur supplements. There has been sufficient research to define, at least in a general way, the areas affected in the United States and Canada. Some data illustrative of the response obtained from sulfur additions in these sulfur-deficient areas are reviewed in this Section.

A. Known and Potential Areas of Sulfur Deficiency in the United States

Locations in the United States where crops have responded to sulfur in field experiments are shown on the map in Fig. 4. There are three general areas.

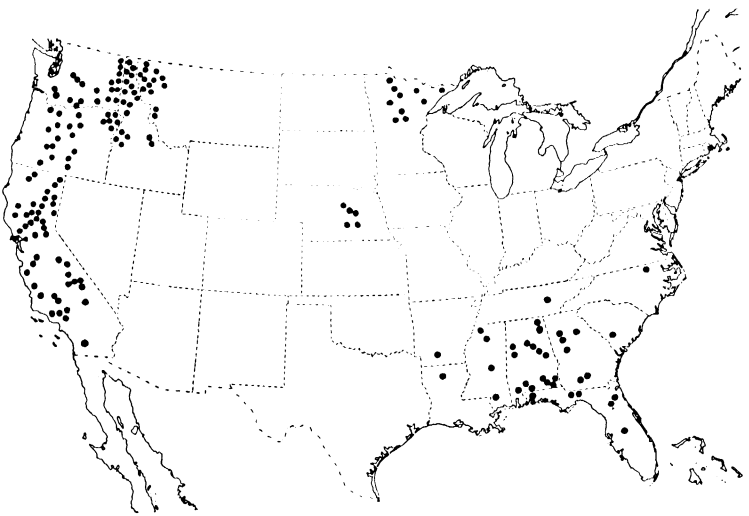

Fig. 4. Locations where responses of crops to applied sulfur have been demonstrated by field experiments. From Jordan and Reisenauer (1957).

1. Pacific Coast and the Northwest

Sulfur-deficient areas are widespread in nonirrigated soils along the Pacific Coast and in the Northwest. The earliest and some of the most pronounced responses to sulfur fertilization in the United States were reported from this area. Sulfur carried in irrigation water generally precludes the need for further additions on the irrigated soils.

Cheney *et al.* (1956) describe the soils and soil management practices in the Pacific Northwest. Nonirrigated soils comprise approximately 75 per cent of total cropland in this area. Sulfur deficiencies are described particularly in several soil zones.

Sulfur deficiencies for legumes are particularly noted in the Chernozem Zone of eastern Washington and western Idaho. Sulfur responses have occurred generally in the higher rainfall area on recropped wheat, especially spring-seeded wheat.

Sulfur deficiencies are also widespread in the Reddish Brown Latosol Zone. In upland areas of this Zone, gypsum was for many years the only fertilizer or soil amendment used extensively. Sulfur is also recommended for legumes and some other crops in lowland areas of this Zone.

Crop responses to sulfur have also been established as widespread in the Reddish Brown Latosol-Noncalcic Brown Zones. Sulfur deficiencies occur in some areas of the Sierozem Zone, but not in others.

Conrad (1950) shows locations in California where sulfur or its carriers have increased growth of legumes, mostly dry-farmed annuals. The locations were widely distributed over the state.

Alfalfa, clover, wheat, barley, and sugar beets have all been reported as benefiting from sulfur applications along the Pacific Coast and in the Northwest.

Rendig (1956) reports that the yield of alfalfa grown on Delhi sand in the San Joaquin Valley of California was more than doubled by applications of 200 and 400 lb. of gypsum per acre. The 400-lb. application was superior to the lower rate only at the first two of five cuttings.

Reisenauer and Leggett (1957) report on the yield response with wheat in a field experiment on Palouse silt loam. There was a positive nitrogen-sulfur interaction. The wheat yield was increased from 18.4 bushels per acre without additions of nitrogen or sulfur to 49.3 bushels where the two were applied in combination. Part of their data is reproduced in Table V.

Tolman and Stoker (1941) obtained a marked response to sulfur in production of sugar beet seed on soils of the Newberg series in Oregon. On treatments with adequate nitrogen fertilization, plots with and without sulfur additions produced means of 1867 and 1317 lb. of sugar beet seed per acre, respectively.

Conrad *et al.* (1947) found that applications of sulfur to certain range areas of Altamont loam in California resulted in three- to four-fold increases in yields of legumes, principally bur clover, *Medicago hispida*, in the first year. In succeeding years, yields of non-legumes were increased by margins up to twofold.

TABLE V

Effect of Applications of Nitrogen and Sulfur on Wheat Yields on Palouse Silt Loam[a]

Nutrients applied		
N (lb. per acre)	S (lb. per acre)	Yield of wheat (bu. per acre)
0	0	18.4
0	1	19.0
0	10	20.7
120	0	27.3
120	1	31.3
120	10	49.3

[a] Adapted from Reisenauer and Leggett (1957).

2. *Southeastern United States*

The soils of the southeastern United States are highly weathered. Native supplies of organic matter are low. Except in the vicinity of a few cities there is only moderate industrial activity to contribute sulfur in combustion gases. These factors combine to make the area one of potential sulfur deficiency. The affected area probably extends northward roughly to the southern borders of Kentucky, Tennessee, and Virginia. As noted in Section IV, B, sulfur in precipitation and atmosphere was considerably higher north of this line than in states farther south. Increased consumption of coal rather than any change in soil conditions probably determines the northern limit of the sulfur-deficient area.

The Southeast has long been a heavy user of commercial fertilizer and it is probable that the sulfur carried just incidentally in these materials has sustained crop production. When sulfur-free fertilizers are used, however, sulfur deficiencies become evident on many soils and within a few years. The first extensive work showing the response of cotton to sulfate was carried out by the Alabama Agricultural Experiment Station from 1939 to 1943 and reported by Ensminger (1950). More recent field trials show responses to sulfur for cotton, clovers, tobacco, and nitrogen-fertilized Coastal bermuda grass (Ensminger, 1957; Jordan and Bardsley, 1958).

Results reported by Ensminger (1950) from field tests conducted in Alabama from 1939 to 1943 at 420 locations show that gypsum increased yields an average of 80 lb. of seed cotton per acre. More recently Ens-

minger (1957) reported on later experiments. Sulfate-free and sulfate-containing fertilizers were compared at 12 locations for periods of one to four years. The mean advantage for the sulfate-containing fertilizer was 161 lb. of seed cotton per acre as shown in Table VI.

TABLE VI

Effects of Sulfate-Free and Sulfate-Containing Fertilizers on Yields of Cotton in Alabama[a]

Soil type	Yield of seed cotton, lb. per acre: Sulfate-free fertilizer	Sulfate-containing fertilizer
Decatur c.l.	1,367	1,597
Decatur c.l.	1,020	1,163
Stough v.f.s.l.	935	1,080
Kalmia l.s.	993	1,149
Kalmia f.s.l.	671	833
Kalmia f.s.l.	1,021	1,239
Greenville f.s.l.	1,510	1,567
Magnolia f.s.l.	1,230	1,374
Magnolia f.s.l.	645	902
Boswell v.f.s.l.	797	870
Boswell v.f.s.l.	554	722
Norfolk l.s.	1,008	972
Weighted averages	1,001	1,162

[a] Data from Ensminger (1957).

In the Southern Regional Sulfur Project for the period 1954 to 1956, mean increases in yields for sulfur applications on representative soils have been reported as in Table VII.

TABLE VII

Mean Increases in Yields on Representative Soils after Sulfur Application[a]

Crop	Increased per acre yield due to sulfur
Cotton	260 lb. seed cotton
Clover	504 lb. dry forage
Clover-grass or grass	396 lb. dry forage
Tobacco	261 lb. leaf

[a] Data from Jordan and Bardsley, 1958.

3. *Middle West*

Soils of the Middle West with their greater accumulations of organic matter have greater reserves of sulfur than soils of the Southeast. Industrial activity is more extensive and widespread. It would not be expected that sulfur deficiencies would be widely prevalent.

There are two major areas in which responses of crops to sulfur have been reported. One is an area of gray-wooded soils of the Nebish-Rockwood association in Minnesota. A second area is in Nebraska on leached sandy soil that is low in organic matter. Responsive crops include alfalfa and clovers.

In Minnesota, a systematic study of the effect of gypsum on alfalfa yields was conducted in the period 1923 to 1926, inclusive (Alway, 1927). Responses were obtained on two fields within the sulfur-deficient area of the state. At Bemidji, gypsum-treated plots yielded 199 per cent, and at Backus, 119 per cent, of the yield of plots not treated with gypsum. Both fields were on Nymore loamy sand.

On a leached sandy soil low in organic matter, Fox (1956) reported yields of alfalfa shown in Table VIII. Only one application of sulfur was

TABLE VIII

Effects of Fertilizer, Lime, and Sulfur on Yields of Alfalfa in Nebraska

Treatments	Yields of alfalfa, lb per acre	
	First year	Second year
None	2400	1500
P, K, lime	6700	3400
P, K, lime, sulfur	8100	6600

[a] Data from Fox (1956)

made in this experiment, and the benefits persisted through a 2-year period.

4. *Other Areas*

There may be other areas of sulfur deficiency in the United States, but they have not been prominently reported in the literature. This would indicate that the deficiencies are neither serious nor widespread. Conversely, studies in a few areas indicate that sulfur supplies are now adequate for sustained production of crops.

An appraisal of the fertility status of New England soils (Northeast Soil Research Committee, 1954) shows that probably much more sulfur is being applied to soils than is removed by crops. Animal manures are calculated to contribute almost as much sulfur to the soil as is removed in harvested crops, while fertilizers add almost four times and rainfall adds three times as much. Coal consumed in the area contributes 13.3 lb. of sulfur per acre to the atmosphere, as an average, each year.

In Indiana (Bertramson *et al.*, 1950), the sulfur balance indicates that under average conditions of crop production, the likelihood of sulfur deficiency is not great. This does not preclude the possibility that local areas may be in need of sulfur applications.

No responses to sulfur applications were found in fairly extensive field experiments conducted in Texas (Reynolds, 1930), Virginia (Lutz, 1957), and Kentucky (Seay, 1957). From a consideration of sulfur supplies and requirements for crops it was concluded that Illinois soils are in no danger of sulfur shortage (Illinois Agricultural Experiment Station, 1937).

B. Sulfur-Deficient Areas in Canada

Gray-wooded soils, which are extensively developed in the provinces of Alberta, British Columbia, and Saskatchewan in Canada are frequently sulfur deficient.

The sulfur needs of these soils have been studied most extensively in Alberta. In this province a majority of the gray-wooded soils which occur in an area generally west of a line from Edmonton to Calgary are sulfur deficient. Sulfur deficiency is more variable in gray-wooded soil areas immediately north and northeast of Edmonton. Bentley (personal communication, 1957) estimates that there may be 5 million and perhaps up to 15 million acres in Alberta alone which are responsive to sulfur fertilization. Breton loam, which is one of the most extensive and seriously sulfur-deficient soil types, has been mapped on more than 2 million acres, and the soil survey is still incomplete.

Sulfur is considered of first importance for legumes on the gray-wooded soils of Alberta, except in the Peace River region. Fertilizers supplying only sulfur do not help cereals or grasses much, but when cereals or grasses follow sulfur-fertilized legumes the benefits are large (Alberta Advisory Fertilizer Committee, 1956).

In British Columbia the gray-wooded soils are found principally in the central interior of the province. C. A. Rowles (personal communication, 1957) reports that sulfur applications on these soils have more than doubled clover yields.

In Saskatchewan the gray-wooded soils occur generally in a band from northwest to southeast in the northern half of the province. Both forage

and seed yields of alfalfa have been materially increased by sulfur additions (Department of Soil Science, University of Saskatchewan, 1955).

C. Increasing Frequency of Deficiency with Time

Historically the organic fraction of soils in humid regions is depleted as the land is placed in cultivation. Depletion continues with continued cultivation until equilibrium is reached. Since reserves of sulfur are principally in the organic fraction, the sulfur content of humid soils generally follows this pattern. The trend may be altered by extraneous additions of sulfur in rain or irrigation water, atmosphere, fertilizers, insecticides, and fungicides.

Applications of sulfur supplements to soils at economic rates are principally of benefit to the immediate crop, but they may have moderate cumulative value. An explanation is suggested by the work of Ensminger (1954) who studied the movement of calcium sulfate band-placed in Kalmia sandy loam to supply 36 lb. of sulfur per acre. In 21 days the sulfate had partially moved below the zone of placement, and in 100 days it had largely disappeared from the 0 to 6 inch zone. There were concurrent increases in the sulfate contents of deeper soil horizons.

In areas where extraneous additions of sulfur in fertilizer have been important in supplying the sulfur needs of crops, a shift to use of sulfur-free fertilizers may cause declining yields in a relatively short time. Twenty-nine uniform field experiments in the Southern Regional Sulfur Project, begun in 1953, compared sulfur-free and sulfur-containing fertilizers. There were no significant yield responses to sulfur in the first year of the study. In 1956, the fourth year of the study, sulfur definitely increased yields in two experiments with cotton, two with clover, two with clover-grass combinations or grass alone, and one with tobacco (Jordan and Bardsley, 1958).

VIII. New Developments May Change the Supply-Requirement Balance

Since a considerable part of the sulfur utilized by plants is supplied just incidentally from extraneous sources, technological developments may change the supply-requirement balance.

Fertilizers which carry little or no sulfur are progressively increasing in use. Ammonium nitrate, anhydrous ammonia, urea, and nitrogen solutions are examples among the nitrogen carriers. The production and use of concentrated superphosphate and to lesser extent of other low-sulfur phosphorus carriers are increasing year by year. These changes will have important effects on supply-requirement balances for sulfur in areas which

have used large amounts of fertilizer, particularly the southeastern United States.

Any change from coal as a source of fuel may result in lower additions of sulfur from combustion gases. The development of water power or the conversion from coal to electricity or gas will cause smaller accretions of atmospheric sulfur for precipitation in rainfall, adsorption by surface soils, or direct use by plants. Transmission of energy through long distances from a central source may change the distribution pattern of sulfur supplied by combustion gases if the new energy source replaces local coal-burning units.

For these reasons the magnitude of these incidental additions should be known and perhaps re-examined from time to time. A planned program for sulfur fertilization should replace dependence on extraneous sources unless these are known to be adequate.

IX. Summary

Although the role of sulfur in soil fertility has been somewhat neglected, considerable information has been published on sulfur in relation to soil fertility and animal nutrition. The information at hand may be summarized as follows:

1. Sulfur is a constituent of two amino acids, methionine and cystine. Methionine is essential in animal nutrition. Cystine is not essential but may complement methionine when the latter is present in deficient amounts.

2. Two important plant growth regulators, thiamine and biotin, contain sulfur.

3. Although sulfur is not a part of chlorophyll, sulfur-deficient plants become chlorotic. Severe sulfur deficiency results in stunted growth and reduced yields.

4. Total sulfur content of plants may approach or exceed that of phosphorus. Vegetable crops such as cabbage, turnips, and onions absorb large amounts of sulfur. Legumes are intermediate in this respect. Corn and grasses have lower requirements.

5. The total sulfur content of soils is variable. In case of surface soils most of the sulfur is in the organic form. Subsurface layers of some soils contain appreciable quantities of sulfate.

6. Sulfates are subject to loss by leaching but certain soils have a capacity to retain sulfates in an adsorbed form. The adsorption capacity for sulfate decreases with increasing pH and decreases with increasing phosphate.

7. The amount of sulfur brought down in rainwater varies with location and season of the year. Much of the sulfur brought down comes from the combustion of coal and other fuels which means that larger amounts are brought down near industrial areas and during winter months. In rural areas of the Southeast only 5 to 6 lb. of sulfur per acre per year are added in this manner.

8. Up to the present most fertilizers have contained enough sulfur to meet the requirements of most crops.

9. For certain crops sulfur is added in insecticides and fungicides.

10. Irrigation water used in the West usually contains enough sulfur to meet crop needs.

11. Plants can take up SO_2 directly through stomatal openings. However, the amount absorbed in this way is not likely to be sufficient to meet the requirements of most plants.

12. Considerable sulfur is lost from soils by leaching and erosion in addition to crop removal.

13. Crop response to sulfur has been reported in three general areas in the United States. Sulfur deficiency may be expected where soils are low in organic matter, where there is little or no industrial activity, where fertilizers are used sparingly or not at all, and where irrigation is not practiced.

14. The trend is toward the use of fertilizers containing less sulfur. The continued use of fertilizers containing little or no sulfur will result in the need for a planned program of sulfur fertilization in many areas.

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CORN PLANT POPULATION IN RELATION TO SOIL PRODUCTIVITY

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I. Introduction

The corn plant is less capable of adjustment to a poor stand than other members of the grass family. Therefore, it is important that the proper planting rate be chosen. Experiences of farmers and crop investigators bear out the truth of the advisory statement, "Plant corn thicker if the land is high in productivity and thinner if the land is low in productivity" (Hume *et al.*, 1908). The purpose of this article is to present the results of research by corn growers and agricultural experiment stations on the question of how thick to plant corn.

II. Response of the Corn Plant to a High Level of Soil Productivity

The amount of plant food available to a plant may be increased in one or both of two ways: (1) the population may be reduced, and (2) fertilizing materials including water may be applied to the soil.

When a corn plant is grown in association with other plants the available food constituents must be shared and growth processes are correspondingly impaired. With adequate moisture and plant food, and with no competition with other plants, the growth of every organ is enhanced (Weaver and Clements, 1938).

A. Large Stalk Growth

Large stalk growth occurs in fields having a high level of soil productivity. Vigorous plants mark the presence of abundant fertility. Until the coming of hybrids, height of corn in the field was prized. Tall corn was credited with being the best corn and the soil was managed so as to promote height. This was justified because height was associated with heavy grain production.

In areas where stalks and leaves of corn constitute a valuable feed, fertilizing for greater yields of the nongrain portions may be justified. In Mississippi Jordan (1951) almost doubled the yield of stover in thinly

planted corn by treating the soil with 60 lb. of nitrogen per acre. An additional 60 lb. of nitrogen did not further increase stover yield, although it did increase grain yield a significant amount. Similar results were obtained in North Carolina by Krantz (1949). While stover yields were increased by fertilization with nitrogen the amount of the increase was less regular and smaller than the increase in grain yield. This is to say, as the fertility of the soil increased, the pounds of grain per pound of stover increased.

Harshbarger *et al.* (1954) working in Illinois found that the application of 200 lb. of 8-8-8 fertilizer before planting followed by 200 lb. of ammonium sulfate applied as a side-dressing increased the yield of stalks and leaves 20 per cent. These larger plants were more productive of grain than those on nearby unfertilized plots.

Although exceptions occur, it is usual to expect larger plant growth to follow fertilization of a soil known to be low in available plant nutrients. It is this response which farmers have learned to expect. The greater size of stems and leaves, in itself, is of less importance than the augmented grain yield which the larger photosynthetic unit makes possible.

B. Heavy Root Systems

Heavy root systems accompany large plant growth on highly fertile soils. Root growth is generally in proportion to top growth. Gile and Carrero (1921) divided the roots of corn plants into two lots. They placed one lot in nutrient solutions deficient in certain elements and the other lot in complete nutrient solutions. Roots in the complete nutrient solutions made the greater growth and had a more bushy habit of growth. Although adequate nitrogen favors root growth, an excess of this element in experimental plots has been found by Holbert *et al.* (1924) in Illinois to be injurious because this unbalanced condition favors invasion by certain root rot organisms. More than enough nitrogen, however, is seldom a problem.

Thatcher (1921) has pointed out the essentiality of an abundance of available phosphorus early in the life of the corn plant to stimulate root growth, and many workers have shown that corn plants grown on plots treated with phosphatic fertilizers require a stronger pull to uproot them than those grown on nonphosphated plots.

Koehler *et al.* (1925) measured root system development by counting leaning plants and by determining their resistance to a vertical pull. They found that the application of 4 tons of limestone per acre decreased the percentage of leaning plants and increased the pull required to uproot the stalks. Hoffer and Trost (1925) have shown conclusively that a balanced nutrient supply is very important in enabling corn plants to resist root rot attack by *Gibberella saubinetii.*

C. Greater Grain Production

Greater grain production occurs on corn plants growing on highly fertile soils. A well-developed plant with extensive leaf area and a large root system is fully equipped for the manufacture of grain forming materials. That this takes place is a matter of common observation. Farmers and agronomists often apply fertilizers to increase corn yields but do not increase the population of plants. They recognize that individual plants will produce larger ears and more grain when a large supply of well-balanced plant food is available. Experience of corn growers from the days when the American Indian taught the early colonists to put a fish under each hill of corn has borne out this truth. Harshbarger *et al.* (1954) in Illinois found that the use of 200 lb. of 8-8-8 fertilizer before planting and 200 lb. of ammonium sulphate applied as a side-dressing increased the grain fraction of silage corn by 13 per cent. In trials at Urbana, Illinois, Bauer *et al.* (1926) obtained an average of 58.3 bushels of corn per acre from untreated plots and a 76.6 bushel yield on plants receiving manure, limestone, phosphate, and potash in a twenty-two-year experiment. These plots were planted uniformly at 12,000 kernels per acre, so the increase in yield was attributable to greater grain production per plant.

A more striking illustration of the increase in grain production per plant as a result of more fertile soil is reported by Bauer *et al.* (1926) from the field at Odin, Illinois. The untreated plots in the single year, 1910, produced grain at the rate of 25.7 bushels per acre and the plots treated with crop residues, limestone, phosphate, and potash yielded 82.8 bushels.

Lang *et al.* (1956) showed that highly productive soil increased grain yield per plant compared with the same number of plants on soil medium to low in productivity. Furthermore, this comparative increase in grain production per plant mounted as plants per acre increased. For instance, at 4,000 plants per acre, the average yield of 9 single-cross hybrids was 45.7 bushels per acre in the low-productive and 54.5 bushels on the highly productive soil, an increase of 19 per cent. When the population was 8,000 plants per acre, the increase in yield of the high- over the low-productive soil was 27 per cent. At 12,000 plants per acre the increase was 43 per cent; at 16,000 it was 84 per cent; at 20,000 it was 129 per cent; and at 24,000 it dropped a little but it was still high, being 118 per cent. Figure 1 shows these differences graphically. These results may be summarized by saying that an increase in the productivity of the soil at any population rate increased the grain produced per plant and this tended to be accelerated as plants per acre increased up to 20,000, beyond which on the highly productive soil it declined somewhat.

Another way of showing this principle is to compare the pounds of

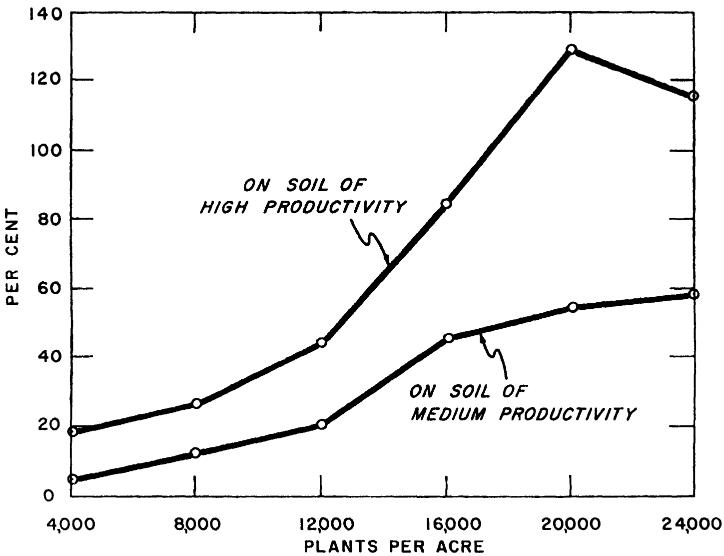

FIG. 1. Percentage increase in grain production per plant brought about by growing corn on soils of medium and high productivity compared with that on soil of low productivity.

shelled corn produced per plant on the three soil fertility levels with which Lang *et al.* (1956) worked. Figure 2 shows that in every case at each population level the yield per plant was higher on the medium-productive soil than on the low; and higher on the high-productive soil than on the medium.

This achievement of increased grain production at high fertility levels is due to three adjustments: (1) the plants may produce two or more ears per plant; (2) the number of ears per plant may not increase, but the size of the ears may increase; and (3) the percentage of stalk barrenness may be reduced. Which of these responses predominates is influenced by the inherent characteristics of the hybrid or variety. Usually all three adjustments occur to some degree depending upon the circumstances.

D. Increased Tiller Production

Increased tiller production accompanies an increase in soil productivity. McClelland (1928a) in Mississippi reported that the amount of available nitrogen influenced sucker production on some 28 varieties whether the nitrogen was from natural sources or applied as nitrate of soda. The amount of soluble nitrogen exerted a greater effect upon tiller production than the amount of moisture in the soil. Williams (1912) in North Carolina

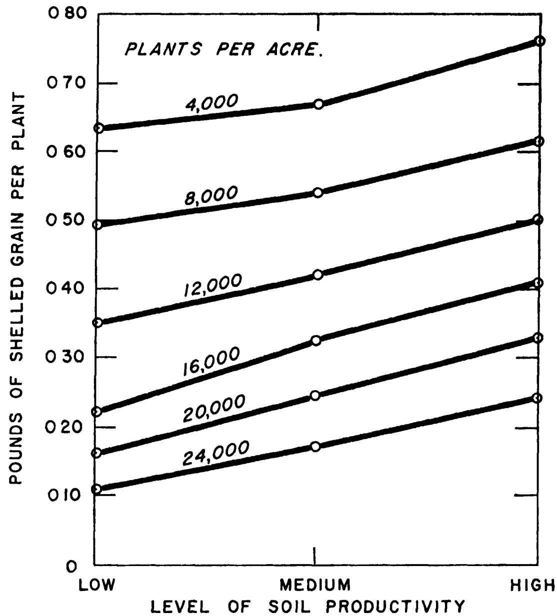

FIG. 2. Influence of soil productivity level on pounds of shelled corn per plant at six populations

also found that the number of suckers which varieties of corn produced seemed to be determined principally by the amount of available plant food in the soil. Lyon (1905) at the Nebraska Station recognized that tillers develop on corn whenever the stand is thinner than the soil or season will support. He observed the tillers have a value in that they thicken up a deficient stand and when well developed they produce ears. In a two-year experiment plants with tillers removed produced 17 bushels less grain per acre than plants with their tillers undisturbed.

III. Plants Gain in Grain-Producing Efficiency as Population Increases

Stalks and leaves of corn to the grain farmer are of relatively little value in themselves. They are necessary because of their functions in connection with grain production. Crop growers are, therefore, greatly interested in producing just as little low value stover and as much high value grain as possible. Stepping the population up per acre is the way to decrease the amount of stover required to produce a pound of grain. However, like most good things, there is a limit to the grain-producing efficiency which

can be achieved in this way. This means that after a certain high efficiency has been reached a further increase in plant population will result in less grain per unit of stover.

Plant population studies were conducted at the Illinois Station with two commercial hybrids differing in length-of-season requirement. U.S. 13 was the full-season and Wisconsin 464 was the short-season hybrid. These were planted in integrated plots at six different rates in eight replications and thinned to 4, 8, 12, 16, 20, and 24 thousand plants per acre. When ma-

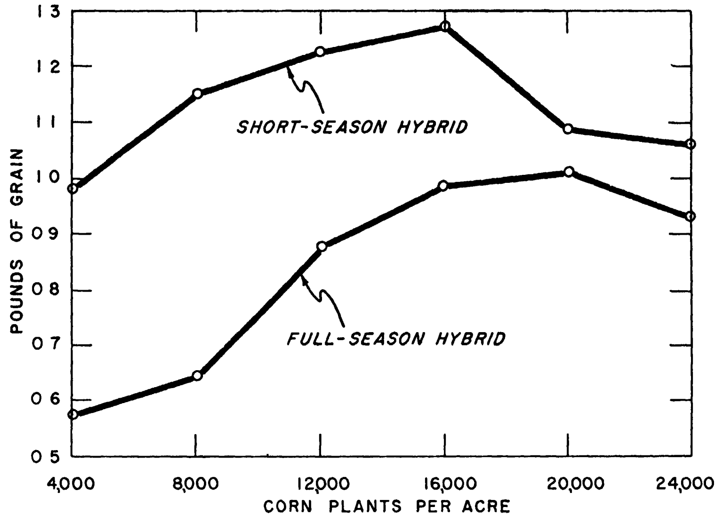

FIG. 3. Pounds of grain per pound of stover produced by a short- and a full-season hybrid when grown at six populations at Urbana, Illinois in 1952.

ture the entire plant was harvested, cured in shocks, husked and yields of grain and stover determined. Efficiency in grain production was ascertained by dividing the pounds of grain produced by the pounds of stover produced per acre. The data are presented graphically in Fig. 3. Two facts are discernible at a glance: (1) the short-season hybrid produced more grain per pound of stover than the full-season hybrid, and (2) grain production per unit of stover increased with plant population up to a peak and then dropped off. The drop in efficiency came at 20,000 plants per acre in the case of the short-season hybrid and at 24,000 plants with the full-season hybrid. The highest yield per acre of both hybrids was at a population of 20 thousand plants. Thus the point of greatest efficiency is at approximately the same population which gave the highest grain yield per acre.

Morrow and Hunt (1889, 1891) found, with open-pollinated corn in

Illinois, that grain production per unit of stover increased as plant population rose from low rates up to a maximum which coincided with the highest grain yield per acre, after which greater plant population was associated with reduced amount of grain per unit of stover. At 7,260 plants per acre (Morrow and Hunt, 1891) each pound of stover produced 0.667 lb. of grain and an acre yield of 55 bushels. At 11,575 plants each pound of stover produced 0.769 lb. of grain and an acre yield of 81 bushels. At 34,530 plants per acre each pound of stover produced 0.278 lb. of grain and an acre yield of 59 bushels. Morrow and Gardner (1892) found that 47,520 kernels drilled per acre produced only one-tenth as much grain as stover, but 15,840 kernels produced .6 lb. of grain for each pound of stover. Jordan (1951) obtained similar results at Caledonia, Mississippi, with corn in plots receiving different quantities of nitrogen. Increasing the nitrogen increased the yield per acre and also progressively increased the proportion of grain to stover. This held at the two populations used, namely, 4,000 and 12,000 plants per acre. Johnson and Webb (1889) in Connecticut obtained results which showed a similar trend although they did not show the close parallel relationship between grain yield per acre and grain production per unit of stover shown by other investigators. They found, however, that the principle which held with dent corn also held with corn of the flint type.

In the central Great Plains Brandon (1937) found that corn planted 30 to 36 inches apart in 44-inch rows averaged about 30 per cent ears; planted 24 inches apart, 25 per cent ears and 12 to 18 inches apart only 20 per cent ears. Eisele (1935) reported from studies in Iowa that corn plants decreased in size markedly as number of plants in the hill increased. The basal area of a stalk in a hill with five stalks was less than half of one from a single-plant hill. Osborn (1925) observed from his experiments in Arkansas that the ratio of stover to grain is influenced by the favorableness of conditions for growth and maturity. When plant food or moisture is short the proportion of stover to grain may be high, but under favorable conditions the stover fraction may be lower in the high- than in the low-population rates.

Thus, the goal of the corn grower seems to be to get a plant population which will produce, under the conditions provided by the climate and soil, a maximum of grain per acre and a relative minimum of stover. Stover has little farm value except for its photosynthetic function during the growing season. As feed it gives bulk to the ration. In silage the stalks and leaves contribute to the value of the feed, but silage with a minimum of roughage and a maximum of concentrate is best. This means that handling the corn crop so as to get the highest grain-producing efficiency from the plants is highly desirable no matter whether the objective is grain or silage production.

IV. Populations Which Give Maximum Grain Production on Soils of High Productivity

Common observation teaches us that widely spaced corn plants produce more grain per plant than those closely spaced. Thin planting is one method of giving corn plants access to extra plant food. As the number of plants increases, competition for materials in the soil becomes greater. Addition of fertilizers and irrigation water can alleviate the struggle for plant food and thus enable a large number of plants to develop to the same size as a small number did before fertilizer was added. Will still more fertilizer continue to accomplish the same results? When will competition for light, space, carbon dioxide, and other growth factors offset the beneficial effects of added plant food? Given a certain level of soil productivity what corn-plant population will produce the greatest yield of grain per acre? Answers to these questions have been sought in experiments in all the corn-growing states and over a period of approximately seventy years. The results differ with type of corn, area in the country, and many other factors. The subject will be discussed by considering experiences in four important corn growing areas of the United States.

A. In the East

Results from numerous experiments under widely varying conditions have demonstrated the interdependence of population and soil fertilization. Krantz (1949) in North Carolina found that on low-nitrogen plots, increasing the plant population from 4,000 to 13,000 did not increase grain yield, but instead lowered it about 7 per cent. On plots supplied with a medium amount of nitrogen, jumping the population from 4- to 13-thousand plants per acre increased the yield 26 per cent, and on land supplied with an adequate amount of nitrogen the 13,000 population produced 46 per cent more grain than did 4,000 plants. On this highly fertilized plot the ear weight per plant was reduced about 55 per cent by thick planting, but this did not offset the increase in number of ears.

Huber (1944) in Pennsylvania stated, "Just as the use of an adapted corn hybrid is a step in the direction of more efficient corn production, a rate of planting adapted to the soil productivity level of a farm is a step in the same direction." Planting at such a rate that ears weigh about 0.5 lb. per plant seems to be more efficient under Pennsylvania conditions.

Innes (1941) working in Jamaica with soils which were somewhat low in potash found that by adding potash fertilizers he was able to step up the yield of grain 10.4 bushels per acre when he used a planting rate of 10,890 kernels. When he doubled the planting rate, the yield increase for

treatment was 22.5 bushels per acre. Genter *et al.* (1956) in Virginia obtained a higher yield of corn grain on fertilized land when he grew 16,000 rather than 10,000 plants per acre.

B. In the Midwest

Richey (1933), from his long experience with corn in the United States, stated that rate of planting should be adjusted to the productivity of the soil. Thatcher (1922) reported from his experience over fifteen years with corn in Ohio that the tendency was for the thin stand to excel during years of low yield and for the thick stand to be at the top during years of high yield. He also stated that land of low productivity should be planted thinner than land of high productivity. Hume *et al.* (1908) conducted corn plant population tests on soil that normally yielded more than 50 bushels per acre and on soil that normally yielded less that 50 bushels. These studies were made in both central and northern Illinois. On soil of the high productivity rating, the highest average yield was 65.3 bushels obtained from a population of 12,480 plants per acre. The highest average yield on the soil having the low rating was 43.4 bushels per acre and this was obtained from a population of 10,920 plants per acre.

Stringfield and Thatcher (1947) in Ohio concluded that as growing conditions became more favorable the optimum stands were higher. Adapted hybrids, as a group, have higher optimum stands than equally well-adapted open-pollinated varieties. The difference between the two optima is, under favorable conditions, 1,800 to 2,000 plants per acre. Duncan (1954) from his experience in Iowa came to the conclusion that neither the soil fertility level nor the hybrid itself can be critically studied unless plant population pressure on soil fertility level is being exerted to a considerable degree.

Lang *et al.* (1956) reported results of experiments involving six population rates on three levels of soil productivity. The highest average yield on high-prouctive soil was 117 bushels an acre with a population of 20,000 plants per acre. The highest average yield on medium-productive soil was 92 bushels which was obtained from 16,000 plants per acre. The comparable figure on low-productive soil was 74 bushels at 12,000 plants per acre. Lang (1956) in discussing the data from these tests emphasized the importance of adjusting rates of planting to the level of expected production. Pendleton *et al.* (1952) grew 9 hybrids at 8,000, 12,000, 16,000, and 20,000 plants per acre on two soils differing in productivity. The average of all rates on the highly-productive soil was 128 bushels per acre and 71 bushels per acre on the medium-productive soil. The highest yield of any hybrid was 155 bushels per acre. This was

on the soil of the higher productive level and at 20,000 plants per acre. The highest yield on the lower productive soil was 90 bushels per acre at a 12,000 plant population. Interestingly enough these two highest yields were produced by the same single-cross hybrid.

C. In the South

Mooers (1933) from extensive research in Tennessee with open-pollinated varieties found that land capable of producing 35 bushels per acre under favorable conditions came nearer producing that yield with 3,000 plants an acre than any other population. Land capable of producing more than 50 bushels required from 5,400 to 6,600 plants per acre to do so. Long (1955) also working in Tennessee, but with hybrid corn, found that plant population should be adjusted to soil fertility for maximum yields. For example, 6,000 plants should be provided for a 60-bushel yield; and 10,000 for a 100-bushel yield. On land capable of producing less than 20 bushels per acre, the population should not be over 3,000 plants per acre.

Thomas (1956) found in Alabama that soil fertilized with 40 lb. of nitrogen per acre gave a yield increase over no treatment of 14 bushels per acre when the plant population was 6,000 per acre, and an increase of 22.7 bushels when the population was 12,000 per acre.

Jordan *et al.* (1950) and Jordan (1951) compared 4,000 and 12,000 corn plant populations at three levels of nitrogen treatment in Mississippi. The 4,000 plant stand gave a substantial yield increase from the first 60-lb. increment of nitrogen, but only a moderate increase from the second 60-lb. increment. In striking contrast, the 12,000 plant stand gave a substantial yield increase over the entire nitrogen range. Production of dry matter increased with increasing nitrogen applications and with the heavier plant stand, thus emphasizing the importance of balancing fertility and stand rates.

D. In the West

Where rainfall is adequate or where irrigation can be practiced, the same general relationship between soil productivity and plant population for maximum corn yield applies as in other parts of the country. However, in the western edge of the Corn Belt the yields are usually limited by a low moisture supply. In such locations as Nebraska Kiesselbach *et al.* (1928) suggested that rate of planting be reduced to the rainfall. Brandon (1937) in the west central Great Plains reported that the highest twelve-year average yield of ear corn was 13.3 bushels per acre which was obtained at a population of 5,940 plants an acre. Lower populations gave larger ears per plant and higher populations gave smaller ears, and both produced less

grain per acre. So, in the West as in other parts of the country, the corn plant population for maximum yield is determined by soil productivity, but in the West productivity of the soil is more often set by moisture supply rather than fertility level.

V. Fertilizing the Soil to Support a High Corn-Plant Population

Corn yield is a function of climate, season, soil, variety, population, available nutrients and culture. Correlating these functions to produce the highest possible yields with the greatest efficiency has been the aim of research workers and farmers everywhere since corn production began. The dynamics that influence the interactions of these functions are difficult to control and this limits the findings of research to a narrow range of conditions. Consequently, few results are fully substantiated. However, some broad general principles have been agreed upon. They are that (1) higher than average yields are secured only with higher than average populations and (2) higher than average populations require higher than average fertility. Such statements are abstract and have little meaning other than to the worker who has related them to his own experience.

Recently Duncan (1954), Krantz (1949), Lang *et al.* (1956), Long (1955), Wofford *et al.* (1956), and Woodle and Williamon (1949) have shown greater increase in grain production from high populations at high fertility levels than at high populations on low fertility levels. This would be expected. The disturbing element is the wide range of populations and fertility levels at which the maximum production was reached. These variances may be related mainly to basic differences in soils.

A. Sandy Soils

Warner *et al.* (1948) working on sandy soils in Florida reached maximum production with 6,000 corn plants per acre on all fertility levels. They found little benefits for additional nitrogen above 40 lb. per acre applied as a side dressing if 20 lb. was applied at planting time.

Horner and Hull (1952) also in Florida secured maximum production at 11,500 plants per acre with early hybrids and 6,000 population with full-season hybrids. Wofford *et al.* (1956) likewise in Florida found that season and dates of planting produced significant interactions in determining results from high populations. In 1955 with 79 lb. of nitrogen there was no increase in yields with populations above 7,000 plants an acre and the optimum date of planting was March 15 to April 15th. In 1956 the maximum yield was reached at 11,000 and 13,000 plants an acre with nitrogen rates of 160 to 200 lb. an acre, and a planting date not later than March 1.

B. Red-Yellow Podzolic Soils

Krantz (1949), Woodle and Williamon (1949), Long (1955), and Thomas (1956) have reported on population-fertility interaction on the soils of the southeastern states. Krantz (1949) found nitrogen to be the limiting factor affecting corn yields in North Carolina. With adequate nitrogen a population of 13,000 plants per acre gave maximum production. The most economical nitrogen level was reached at 120 lb. per acre. If the corn crop was preceded by a crop that was heavily fertilized with phosphorus there was little or no response to further applications of that element. If phosphorus was low that nutrient had to be supplied. Response to potash depended on the potash level of the soil. Soils having less than 100 lb. of exchangeable potash per acre responded to treatment with potash.

Long (1955) in Tennessee using populations of 8,000, 12,000 and 16,000 plants an acre along with 60, 90, and 120 lb. of nitrogen concluded that 12,000 plants per acre was optimum and that 90 lb. of nitrogen was adequate where phosphate and potash were sufficient. Thomas (1956) found on a Dewey silt loam in Alabama, with pH of 6.8 and adequate P and K, that 12,000 corn plants per acre gave maximum production, irrespective of added nitrogen. Woodle and Williamon (1949), studying the corn growing programs of farmers in South Carolina, found that increasing population was the first step to higher corn production. As plants per acre increased from 5,000 to 12,000, yields progressively rose from 33 to 74 bushels per acre. Increasing the population was followed by increased fertilizer rates. Nitrogen was the most important of the nutrients applied. Augmenting nitrogen rates from 24 to 100 lb. per acre increased yields of corn from 39 to 81 bushels per acre or 107 per cent. Increasing the amount of P_2O_5 applied from 25 to 60 lb. per acre boosted the yield 52 per cent, and likewise increasing K_2O from 15 to 50 lb. per acre gave yield increases equivalent to 57 per cent. This study showed that farmers side-dressed the larger part of their nitrogen and started early when the corn was 12 to 18 inches high. In many cases additional applications were needed until the corn was ready to tassel.

C. Corn Belt Soils

In the midwest corn belt area Duncan (1954) conducted four experiments on widely different soil types with varying corn plant populations, fertility levels, and hybrids. Yield differences resulting from increasing plants per acre from 8,000 to 24,000 ranged from a loss of 22.7 bushel on low fertility to a gain of 64.8 bushels per acre on high fertility. Duncan found that late hydrids out-yielded the medium maturing hybrids up to

16,000 population, but above this rate medium maturing hybrids were as good or better.

Stringfield and Thatcher (1947), Seem and Huber (1947), and Pendleton *et al.* (1952) have pointed out in various ways that testing hybrids at low populations on low fertility levels fails to bring out the critical capabilities of corn hybrids or to permit them to make full use of plant foods. Stringfield (1953) later pointed out that season had more influence on population optima than hybrids. This could easily account for the wide variability of the results obtained by workers in this field. Unfortunately few studies with population-fertility interaction have been conducted long enough to secure full information on season interaction.

Comparing the tolerance of single crosses, WF9 × C103 and Hy2 × Oh7, to thick planting at Urbana, Pendleton *et al.* (1952) found a wide variation between seasons. Adapted double-cross hybrids at Illinois did not show wide variation in grain yields. From 1943 to 1954 five hybrids were grown across all fertility levels of the Morrow Plots. Each hybrid was planted in plots 2 rows wide and 10 hills long with 40-inch spacing between hills and with 3 plants per hill to give a population of 12,000 plants per acre. Each plot was replicated four times on each fertility level each year. Hybrid U.S. 13 was used because of its apparent ability to produce and perform well on highly productive soils. Illinois hybrid 972 was selected because of its apparent wide adaptability. Each of the other three hybrids varied from U.S. 13 by only one inbred. Over the period of twelve years no one hybrid varied in its average yield by as much as one bushel from the average of all five hybrids.

D. Dry Climate Soils

Pumphrey and Harris (1956) studied the effect of nitrogen fertilizer on corn production when used in conjunction with irrigation on the dry lands of Nebraska near Scotts Bluff. They found that low nitrogen limited corn yield on irrigated Tripp very fine sandy loam. During favorable growing seasons increases of 33, 54, and 71 bushels per acre were secured by the use of 40, 80, and 120 lb. of nitrogen, respectively. Plowing under, applying at planting time, or side-dressing in the early stages of growth were more effective than applying nitrogen during later growing periods. Pumphrey and Harris (1956) also measured the residual effect of nitrogen applied for a previous corn crop and found that losses of nitrogen by leaching were not great in an irrigated Tripp fine sandy loam.

Inadequate available nitrogen seems to be the limiting factor causing low yields of corn when dry-climate soils are irrigated. This was substantiated by Lyon *et al.* (1944) and also by Olson and Fitts (1941).

E. European Studies

In corn-growing areas of Europe, as reported by Jugenheimer *et al.* (1953) and Jugenheimer and Silow (1954), workers have found that populations required for maximum production are nearly double those used in the United States. The average recommended rate is 5 to 7 plants per square meter or between 25,000 and 30,000 plants per acre. Even higher populations than this do not decrease yields as they commonly do in the United States.

F. Discussion

Fertilizing for high populations is well summarized by Martin (1957) "Good fertility is essential for high yields especially when corn is grown in thick stands." The climate and soil resources must be intelligently appraised before plant stands and fertilizer treatments for maximum yields can be determined.

Many workers studying corn populations have a feeling that findings in this field are inadequate. This is easily understood in the light of the wide variations that exist in their findings. The question might be asked here: can findings ever be adequate as long as so little is known about why yields are so adversely affected by increases in population above a relatively low level? Practically all data show that yields go down when populations are increased above a certain level, even though known environmental factors including nutrients and water are controlled. Evidence indicates that present day corn hybrids have inherent production capabilities far beyond that which has been achieved.

To illustrate these concepts Fig. 4 has been constructed from data presented by Lang *et al.* (1956) for the hybrid, WF9 × 38-11. This figure indicates that there are unknown yield inhibitors which must be circumvented before further work on the interaction between population and fertility level can do more than be specific to the local environment. When the hybrid, WF9 × 38-11, was planted in an environment conducive to high production, with competition between plants eliminated by growing only one plant per area of 40 inches by 40 inches, it produced 64 bushels per acre, thus demonstrating its genetic capabilities. If one plant per 40 × 40-inch space or 4,000 plants per acre can produce at the rate of 64 bushels then it is reasonable to believe that 2 plants in the same area could produce 128 bushels per acre and so on ad infinitum. With 8 plants per area of 40 × 40 inches the yield could conceivably exceed 500 bushels per acre. When Lang *et al.* (1956) grew two or more plants per 40 × 40-inch area the yields were very disappointing and failed to follow the yield potential of the hybrid. Raising the fertility level contributed a little improvement

but the differences were still so striking that the improvements lost their significance in comparison with the effect of the unknown. What is the unknown phenomenon placing a barrier to top corn yields which science has been unable to fathom?

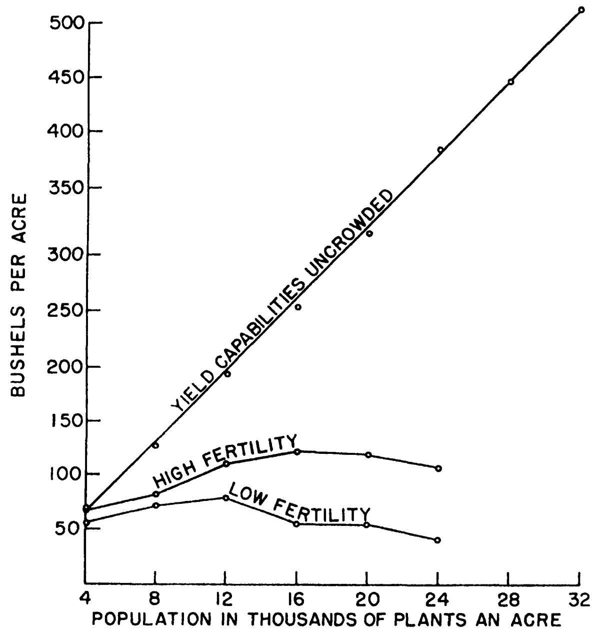

FIG. 4. Yield capabilities of WF9 × 38–11 single-cross hybrid at high fertility level and actual yields at high and low fertility levels when crowded.

Miller (1956), working with E. B. Earley in Illinois, placed light control structures over individual corn plants when they were 40 inches high and let them remain until the corn was mature. The object was to determine if light was a factor in the competition between plants at high populations. The experiment was conducted on a highly productive soil at the Agronomy South Farm, Urbana. The results are given in Table I and show that grams of grain per plant were reduced as light was withheld from the plant.

Miller (1956) states that the effect of reduced quantities of sunlight on the growth and development of corn plants in many ways parallels that which is found at high population rates. This points, then, to lack of solar energy as the factor which inhibits the photosynthetic processes so necessary for full expression of plant capabilities. However, in some cases plants

TABLE I

The Effect of Light on Grain Production of Dent Corn

Sunlight admitted (%)	Average yield of grain per plant (grams)
100	276.3
70	256.7
40	237 7
10	31 0

seem to be hindered less than in others by shading. This makes it appear that light is not the critical factor. Is there some other factor which operates to set the level of yield under high populations? Yes, there is. It appears to be soil organic matter.

Green *et al.* (1957) in Florida showed that sandy soils failed to support high populations irrespective of fertilization and water, whereas muck soils supported a much higher optimum population in the same area. Workers in Tennessee, North Carolina, South Carolina, and Alabama have reported optimal population above those obtained on sandy soils, but lower than those of the corn belt, as published by Lang *et al.* (1956) and Duncan (1952). Duncan reported a higher population optimum in Northern Iowa than Lang *et al.* (1956) in Illinois. Good European farmers use populations almost double those used in the United States. Fertilized soils in Florida, the cornbelt, and Europe differ most in their content of organic matter. There appears in all of the findings a close relationship between organic matter content of the soil and optimum populations for highest production.

VI. Changes in Plant Characters Associated with Higher Population Rates

Many adjustments are made by corn plants to an increase in population. On highly productive soil the net result of moderately high population rates is an increase in acre yield of grain, but other changes occur, some of which are not beneficial. A number of these will be considered in the next few pages.

A. Size of Ear

Weight of ear decreases with increased population in all experiments, except in the case of hybrids or varieties which tend to produce more than one ear at low population levels. Perhaps, a more nearly correct way to

express this rule would be to say that weight of grain per plant decreases with increased population. Lang *et al.* (1956) obtained ears averaging 0.71 lb. at a population of 4,000 plants and 0.29 lb. ears at 24,000 plants per acre. An ear weight of 0.54 lb. was obtained from 12,000 plants per acre which corresponded to the highest average yield for all hybrids at all fertility levels. Huber (1944) of Pennsylvania and Stringfield and Thatcher (1947) in Ohio stated that a population resulting in an ear weighing about 0.5 lb. indicates efficient use of the land. Hunter and Yunger (1955) of Oregon found that maximum yields obtained were associated with ear weights of 0.52 to 0.57 lb. Miles (1951) obtained maximum corn yield in Indiana at 14,224 plants per acre and an average ear weight of 0.54 lb. When the population was 24,890 the ear weight was only 0.31 lb. To show the relationship between plant population on productive soil and ear weight per plant, data from three states have been combined and presented in graphic form (Fig. 5). Results reported by Duncan (1952) in Iowa, by Miles

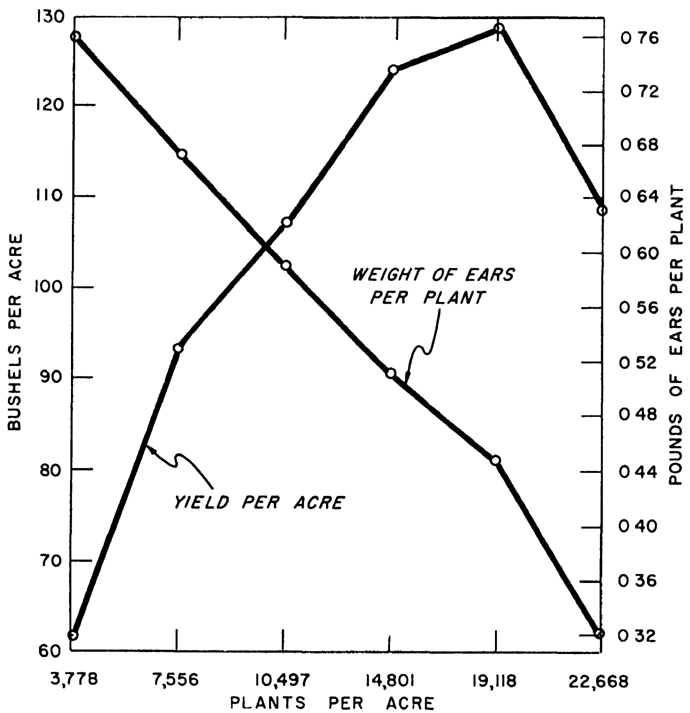

FIG. 5. Influence of corn plant population when soil is highly productive, on yield of grain per acre, and on weight of ears per plant.

(1951) in Indiana, and Lang *et al.* (1956) in Illinois were used in preparing this figure. As long as the yield per acre increased with mounting population, the reduction in weight of ears per plant declined linearly but when the population passed the optimum for maximum yield per acre, the grain production per plant dropped sharply. The population which gave the highest yield was approximately 20,000 plants per acre and the average weight of ears per plant was 0.45 lb.

Ear weight per plant cannot be applied in the same way in all parts of the country as an index to optimum rate of planting. In the central corn belt, half pound ears per plant are associated with highest grain producing efficiency, but in states growing smaller hybrids a smaller ear will give the highest yield. Rost (1953) in Minnesota obtained the highest yield of grain at a population of 31,360 plants per acre and an ear weight per plant of 0.36 lb. In areas where multiple-eared corn is grown ear size may be much lower than where single-eared types are grown. A more correct criterion has been applied in this discussion. This criterion is the weight of ears per plant rather than the average weight of individual ears.

Losses in mechanical harvesting of small ears tend to discourage extremely thick planting. Shelling of kernels from small ears is greater than from large ones.

B. Number of Ears per Stalk

The number of ears per stalk is determined by heredity and also by environment. Prolific strains produce multiple ears even under relatively unfavorable growing conditions. Single-eared hybrids vary widely in their tendency to produce more than one ear under high fertility and low-population levels. Lang *et al.* (1956) in tests at Illinois reported that of any of the 9 hybrids in the tests the two single-cross hybrids, Hy2 × OH7 and WF9 × OH41, showed the greatest tendency to be multiple-eared at 4,000 plants per acre and had the lowest percentage of barren stalks at 24,000 plants per acre. Single-cross, WF9 × C103, on the other hand, exhibited the least number of second ears at low population levels and the greatest number of barren stalks at high populations.

Lang *et al.* (1956) found that stalk barrenness was affected more by population than by hybrid or fertility level. Dungan *et al.* (1938) in tests conducted in northern Illinois found 1.2 per cent barrenness with 8,000 plants per acre, 9.3 per cent with 12,000 plants, 15.7 per cent with 16,000 plants, and 23.6 per cent with 20,000 plants per acre. The average number of ears per stalk was 1.01, 0.91, 0.83, and 0.81, for the various populations, respectively.

Eisele (1935) grew corn in 1-, 3-, and 5-plant hills in Iowa. Every stalk

in the one's produced a large ear, and about half of them produced two ears. Not every plant in the three's produced an ear, and ears were formed on less than 75 per cent of the plants in the five's. Enzie (1942) in New York working with sweet corn found that a population of 14,530 plants per acre produced more second ears than any higher number of plants per acre.

C. Composition of Grain

Considerable work has been done with corn plants to determine the influence of stand on composition of the grain, particularly its content of protein and oil. Earley and DeTurk (1948) and Lang *et al.* (1956) found in Illinois that on each level of soil nitrogen the percentage of protein in the grain decreased with increasing field stand. Zuber *et al.* (1954) obtained similar results in Missouri where increasing the plant population caused a slight decrease in crude protein content. Their results suggest that increased grain yields may be an insufficient measure of the effects of increasing stands. Genter *et al.* (1956) in Virginia reported that protein content of corn grain averaged higher at the lower planting rates. Highest yield of protein in pounds was obtained from the higher plant stand and the heaviest application of nitrogen.

Prince (1954) studied the influence of population on the composition of protein in corn grain. He found that increasing the plant stand decreased the total leucine content, but that this decrease was not so great in crude protein content. Thus, the net effect of population rise was to increase the percentage of leucine in the protein. Tryptophan tended to decrease with heavier plant stands. The zein fraction tended to increase faster under thin stand conditions than did total crude protein. Increasing the plant stand tended to increase the total amount of isoleucine as well as its percentage in the crude protein.

Lang *et al.* (1956) in Illinois reported that the oil content of grain decreased with population increase. This was true at populations above 12,000. Genter *et al.* (1956) in Virginia did not find any appreciable effect of plant population on oil content.

D. Height of Plant and Ear

Stringfield and Thatcher (1947) found in their tests in Ohio that the ear node was somewhat higher on thickly planted corn. Plants in hills of 5 stalks had ears 3 inches higher than plants in hills of 3 stalks. Tests in Illinois showed little difference in total plant height as a result of population; however, there was a tendency for plants at 12,000 plants per acre to be slightly taller than those in lower and higher populations. Eisele

(1935) in Iowa found that rate of planting did not significantly modify plant height. Basal area of stalks at maturity grown in 5-plant hills was less than half that of stalks from 1-plant hills.

E. Rate of Development

Increasing the population tends to retard plant development slightly. Stringfield and Thatcher (1947) reported that in Ohio the silking period for a stand of 5 plants per 42 inches of row was roughly 2 days later than for a stand of 3 plants. Lang *et al.* (1956) found in Illinois that silking was delayed 1 day for each additional 4,000 plants per acre. Dungan *et al.* (1938) determined the moisture content of the grain from a rate-of-planting experiment in northern Illinois. They found that the shelled kernels from 8,000, 12,000, 16,000, and 20,000 plants per acre contained, respectively, 19.3, 20.2, 20.8, and 21.2 per cent moisture at the time of harvest.

Enzie (1942) working with 3 varieties of sweet corn in the state of New York found that the plants matured most rapidly when grown in the largest space allotment; namely, in 36-inch check rows with 3 plants per hill (14,520 plants per acre). They matured the slowest when planted in 30-inch rows with the plants spaced 9 inches apart (23,232 plants per acre).

Planting rates in excess of the capacity of the soil to provide plant food and moisture, often cause premature dying of the lower leaves and thus appear to bring on early maturity. This condition, however, does not represent true maturity.

F. Interval Between Tasseling and Silking

Increasing the population density delays plant development. Seed producers have noted this phenomenon and have suspected that silking is delayed more than is tasseling. A study was made of the dates of the half-tassel and the half-silk stage of 9 hybrids in rate-of-planting tests in central Illinois. The results are summarized in Table II.

The increase in time between silking and tasseling due to thick planting was not great. It amounted to only a little over one day when the population was jumped from 8,000 to 20,000 plants per acre.

Unpublished results of Leng in Illinois showed that the spread between tasseling and silking varied widely between hybrids and also between seasons. The interval was found to be much greater at populations above 20,000 than it was at or below this figure. The time between tasseling and the full-silk stage was much greater than that between tasseling and the half-silk stage. Retardation of silk emergence may be looked upon as

TABLE II

Average Day in July When Corn Plants Growing in Different Populations Were in the Half-Tassel and the Half-Silk Stage of Development, Urbana, Illinois, 1950

Population (plants per acre)	½ tassel (day in July)	½ silk (day in July)	Interval between tasseling and silking (days)
8,000	25 85	27.55	1 70
12,000	26 55	28 70	2 15
16,000	26 80	29.20	2.40
20,000	27 70	30 50	2 80

an operation of plant adjustment to high population which in extremely thick stands would bring about complete barrenness.

G. Production of Suckers

Corn suckers (tillers) are familiar to everyone associated with the growing of this crop. Factors which favor the production of suckers, as listed by Williams and Etheridge (1912), are (1) highly productive soil with adequate moisture supply, (2) a strain of corn having a high tillering habit, (3) thin spacing of plants, and (4) a time of planting which is favorable for vigorous growth. Tillering is the response of the plant to environmental conditions which can support a larger population than is present. Suckers are, therefore, more numerous at low than at high population levels on highly productive soil.

Montgomery (1909) in Nebraska reported that many suckers which were formed early in the season disappeared during the period of ear formation. With corn in 1, 2, 3, 4, and 5 plants per hill he found on the tenth of July, 201, 105, 63, 44, and 27 suckers per hundred plants, respectively. By October 1 these tillers had disappeared to the extent of 11, 26, 50, 79, and 96 per cent, respectively, for the 1-, 2-, 3-, 4-, and 5-plant hills.

Miles (1951) in Indiana, and Stringfield and Thatcher (1947) in Ohio found that at optimum stands for grain production sucker number was relatively low.

Many investigators have found that the removal of suckers is of no practical advantage. Thompson *et al.* (1930) in experiments on Long Island found that removal of suckers from sweet corn tended to reduce the yield of marketable ears, especially in the case of sucker removal after the plants had begun to tassel.

Dungan (1931) and Rosenquist (1941) working with corn, and Bartel *et al.* (1935) working with sorghum found that tillers in addition to producing grain themselves may contribute to grain formation on the main stalk under some conditions. So it would seem that suckers play a part in grain production. Their presence in considerable number indicates that plant population is below the optimum for the production of maximum yield.

H. Leaf Area

Eisele (1935) grew corn which was thinned to 1, 3, and 5 plants per hill. An average plant in the 5's had 30 per cent less leaf area by July 1 than one growing singly in a hill. This would mean that the combined leaf area of 5 plants in a hill would be 3 1/2 times that of a single plant in a hill. The maximum leaf area was reached by plants in thin stands much later because of the firing of the lower leaves of plants in the thicker stands. The firing began as early as July 15.

Because of the greater transpiring surface, corn (Eisele, 1938) usually had less available soil moisture at thick than at thin planting rates, especially during July and August in dry seasons. Relative humidity in the corn field during the day was from 3 to 5 per cent lower with 1 plant per hill than with 5 plants, but at night the relative humidity was higher in the thinner planting rates. The rate of evaporation from exposed porous porcelain atmometer cups was 22 per cent greater during July and August with 1 plant per hill than with 5 plants. Aikman (1930) also found that the evaporation rate from the soil among plants in a thin stand was higher than in a dense stand. In general, he found that the denser the stand the higher the humidity, the lower the evaporation rate among the stalks, and the less sunlight reached the lower leaves.

I. Ease of Lodging

Increasing corn plant population on soil of the same productivity decreases the strength of stalks and increases the likelihood of lodging. Koehler *et al.* (1925) stated that 2 plants per hill stood better than corn planted 3 per hill. Kiesselbach *et al.* (1928) found that corn plants growing 5 plants per hill lodged 65 per cent more than those in 1-plant hills. Dungan *et al.* (1938) reported that 8,000, 12,000, 16,000, and 20,000 plants per acre lodged 22, 31, 39, and 46 per cent, respectively.

High incidence of lodging is one of the hazards of increasing population to get maximum yields. Stringfield and Thatcher (1947) stated that the most serious effect of heavier stands is the higher incidence of stalk breakage. A frequent winner in corn yield contests observed after a successful season, "I think I shall drop out of the contest next year. I am get-

ting tired of picking my corn off the ground." That is an extreme situation. Modern lodging-resistant hybrids do not fall over except under severe conditions. The fact still remains, however, that when any lodging occurs, the thick stands will show more of it than medium and thin stands.

VII. Distribution of Plants

In a discussion of rate of planting, questions on width of row, hill planting versus drilling, losses from uneven stands and related matters usually come up. The next few pages will be devoted to the presentation of results from field research on these subjects.

A. Drill-Row Versus Check-Row Planting

Many experiments have been conducted in which a comparison was made between drilled and hilled corn. Morrow and Hunt (1891) found that check-row planting outyielded drill-row corn, but the authors attributed the larger yield to fewer weeds. Results of other tests in Illinois (Burlison, unpublished) over a five-year period showed an average yield of ½ bushel per acre in favor of checking, but in two of the five years drilled corn outyielded that in check rows. Early trials in Indiana by Latta (1889) gave three-year average results slightly in favor of hilled corn. In later tests in Indiana (Kohnke and Miles, 1951) and in other states including Kentucky (Roberts and Kinney, 1912), Ohio (Williams and Welton, 1915), Nebraska (Kiesselbach *et al.*, 1935), Maryland (Patterson, 1899), and Michigan (Rounds *et al.*, 1951), the average yield from comparable populations was in favor of the drill method of planting. The over-all average of results from seven corn growing states covering a total of 39-station years shows a weighted average yield for drilled corn that is 1.6 bushel per acre or 3 per cent above checked corn. This figure is hardly significant economically or statistically.

Other considerations are more important than yield of grain in deciding which method to use in planting corn. In days when animal power was used generally, cultivation to control weeds, especially the first cultivation, was tedious and slow. In order to facilitate weed removal cross cultivation was practiced. This, of course, meant planting the crop so that normal width rows ran in two directions. Extra planting equipment and extra labor in planting operations were required. These were believed to be more than justified by the greater yield made possible by reduced weed competition. Today, power equipment permits more rapid tillage and more timely weed control. Herbicides can be used to reduce the urgency of early cultivation as well as to reclaim a field in which extraneous plants have gained the upper hand. Consequently the practice of check-

row planting is declining in popularity. Also, because handling the check-row wire at planting time considerably slows up operations, very little corn in the corn-belt states is now checked.

Drilling corn has two disadvantages. Corn plants growing singly in the row tend to tiller more than when they are grouped in a hill. Kohnke and Miles (1951) reported 4 times as many suckers in drilled corn spaced 13⅓ inches apart in the row as in corn planted three in a hill in 40-inch rows. Although removal of suckers is somewhat detrimental to yield, planting corn so as to favor sucker production is not an economical method of increasing grain yield.

The other disadvantage is in case of lodging. Miles (1951) stated that hilling was superior to drilling because hilling produced about the same yield and the corn stood much better. For each 3 plants of checked corn that lodged there were 5 plants of drilled corn on the ground.

In order to take advantage of the reduced number of suckers and greater standability of checked corn and to avoid tedious planting procedures, corn growers quite generally use the hill-drop system. It consists of dropping two or three kernels at regular intervals of 28 or 30 inches in the row without any attempt to make the plants form crosswise rows. It is drilling two or three kernels per drop instead of one. This system results in less lodging than drilling. Also, it facilitates harvesting with mechanical equipment because there are fewer plants per hill than with the regular check-row method.

B. Uniform Distribution Versus Hill Grouping of Plants

Spacing corn plants in rows 3½ to 4 feet apart was practiced by pioneers in our country because that distance between rows was the most convenient for tillage and harvest operations. Thinking farmers and others have often raised the question as to whether this system is the most suitable from the standpoint of the plants. The plants in a hill are rarely of equal size. Is it the competition between plants that makes one plant decidedly smaller than the others? Would a smaller plant have fared better if it had been grown singly with a share of land to itself? These questions have given rise to a number of experiments designed to provide the answers.

Bryan *et al.* (1940) in Iowa reported the results of a four-year test in which plants grown 4 per hill in 42-inch rows were compared with plants grown 1 per hill in rows 21 inches apart in both directions. The population was 14,224 plants per acre. The average yield of grain per acre was 80.4 bushels for the 21-inch spacing and 77.3 bushels for the 42-inch spacing. The 42-inch spacing had a distinct advantage in lodging resistance. Collins and Shedd (1941) in Iowa reported the results of comparison made over an eight-year period between plants grown 4 per hill at 42 × 42-inch spac-

ing and plants grown 1 per hill at 21 × 21-inch spacing. The average yield of 21 × 21-inch spacing was 68.2 bushels per acre and that of 42 × 42-inch spacing was 59.8 bushels per acre, a difference of 8.4 bushels. A comparison between plants grown 2 per hill at 30 × 30-inch spacing and plants grown 1 per hill at 30 × 15-inch spacing showed only 0.2 of a bushel difference as a four-year average. Pfister (1942) in Illinois compared the cost of growing corn in hills spaced 20 inches apart in 20-inch rows with checked corn in hills spaced 40 inches apart each way. He used a disk to prepare the seed bed for the corn in 40-inch rows and a field cultivator for the closely spaced corn. He used a cultivator for the 40-inch rows, but used a harrow and a weeder on the other corn. The cost per acre was $4.15 for conventional check-row corn and only $1.80 for the closely spaced corn. Yields, which represented an average of three-years' tests, were 67.0 bushels and 93.7 bushels per acre, respectively, for these two methods.

Dungan (1946) in Illinois grew corn in single-plant hills and multiple-plant hills at different population levels. The greatest advantage of single-plant hills was obtained at relatively high plant population rates. Yields in single-plant hills were significantly superior on productive soil in seasons with a well-distributed and plentiful, though not excessive, rainfall. In seasons with dry weather occurring during July and August the 40-inch rows with corn in the hill produced practically as much grain as the same number of plants per acre singly spaced. It appears from this experience that in seasons when the factor limiting grain yield is rainfall, planting in multiple-plant hills will produce just as high yields as will uniformly distributed plants. But, on the other hand, in seasons with ample rainfall when soil fertility is the limiting factor, uniform plant distribution will produce a larger yield than hill-planted corn. Haber (1927), working with sweet corn in Iowa, found that check-row plantings yielded decidedly better than did drilled corn in a season characterized by a deficient supply of moisture beginning at the time of tasseling and silking. Huelsen (1942) found that the yields from drill-row plantings of sweet corn were extremely low in 1930 in Illinois, indicating that drilled rows may not be so well adapted to dry seasons as checked rows. Roberts and Kinney (1912) found in Kentucky that in a dry year field corn planted in hills yielded better than drilled corn. In 1910, a favorable year, drilled corn was better than checked corn.

Some of the record yields of corn in the nation have been made by closely spaced plants grown singly in the row. Paul H. Peabody in central Illinois grew 191.64 bushels of field corn per acre. This up to 1942 was the highest yield that had ever been attained in the 10-acre yield contest sponsored by the Illinois Crop Improvement Association. Kinney (1943) reported that Peabody grew his corn in 28-inch rows with plants an aver-

age of 13 inches apart in the row. The population was 17,231 plants per acre. Rainfall in 1942 was adequate during July and August for maximum plant growth. Ratliff (1955) in Mississippi grew 304.38 bushels on one acre, using a population of 26,136 plants per acre in 30-inch rows with plants spaced 8 inches apart. The season of 1955 was so favorable that even though equipment and water for irrigation were available no water was applied.

Even though uniform distribution of plants is apparently the best from the standpoint of grain production under ideal moisture conditions, this method of growing corn has some disadvantages. Plants lodge worse than those in multiple-plant hills in spite of the fact that the diameter of the stalks is larger. Plants in single-plant hills sucker more than those in multiple-plant hills.

C. Effect of Missing Plants and Missing Hills

Influence of irregular and deficient stands of corn varies greatly in different parts of the country. In North Dakota, Olson (1928) found that the yield was reduced in almost exactly the same ratio as the reduction in stand. In Nebraska, Kiesselbach *et al.* (1935) conducted extensive tests with irregular numbers of plants per hill but with the same population per acre. They found that a uniform stand of 3 plants per hill produced a fourteen-year average yield of 49.9 bushels per acre; stands of 2 and 4 plants per hill alternating regularly gave a yield of 50.6 bushels; 1, 3, and 5 plants per hill yielded 49.3 bushels per acre; and 1, 2, 3, 4, and 5 plants per hill in regular sequence gave a yield of 50.0 bushels per acre. A precise distribution of plants was not essential under Nebraska conditions. Corn plants adjoining a hill of 1 or 2 plants compensated for the reduced population to some extent, and, of course, the plants present in a hill of reduced stand enhanced their production beyond that of the average plant in a full stand.

Dungan and Nelson (unpublished) conducted experiments in central Illinois for a period of twelve years on the effect of missing plants and missing hills of corn. They found that in a 3-plant per hill population 43 per cent of the loss in grain yield due to a missing hill was made up by an increase in the yield of the 4 nearest hills. When 2 plants were missing, the remaining plant and the 4 nearest surrounding hills compensated for 68 per cent of the loss. When 1 plant was missing, the remaining 2 plants and the 4 nearest neighboring hills restored 89 per cent of the loss. Brewbaker and Immer (1931) in Minnesota also found that hills adjacent to blank hills or to hills with reduced stand yielded more than hills surrounded by a full stand. For instance, at University Farm in 1928, the average yield of a 3-plant hill when adjacent to two blank hills, one blank

hill, and one 2-plant hill was increased 12.6, 7.0, and 4.8 per cent, respectively, over the yield of 3-plant hills which had competition on all sides. Under the conditions of these tests, it appeared that corn plants adjoining a gap or reduced population were able to go a considerable way in compensating for the stand deficiency yet they were never able to fully replace the loss in grain yield.

D. Level Planting Versus Planting in Furrows and on Ridges

In attempts to provide optimum environment for corn plants, various planting practices have been used. For instance, in areas where drought commonly limits yields, corn has been planted in deep furrows (listing) without plowing, or in shallow furrows after plowing. Planting in deep furrows, especially in heavy soils in Iowa, retarded plant development but increased resistance to lodging, according to Jenkins (1934). The yield of grain per acre did not differ significantly from that of level-planted corn or from that of corn planted in shallow furrows. Results in Illinois (Burlison, unpublished) showed that corn drilled in shallow furrows produced the same 5-year average yield as corn drilled on the surface. Drilling in shallow furrows has been found advantageous in weed control because comparatively large grass weeds can be readily covered with soil during cultivation.

An average of eleven years' results in Nebraska (Kiesselbach *et al.* 1935) showed that surface-drilled corn yielded 34.9 bushels per acre, listed corn yielded 34.7 bushels per acre, and corn planted behind furrow openers yielded 32.0 bushels per acre. These small differences were not significant. Quesenberry (1922), on the other hand, found that seed dropped by hand in furrows in New Mexico gave decided increases over that planted with a planter. Brown and Lovett (1938) in Louisiana reported that roots of corn planted in furrows were not as well distributed through the soil between rows as those of surface-planted corn.

In some parts of the southern corn-growing area of the United States farmers ridge their corn at the last two cultivations. This is done for two important reasons, namely, to cover weeds growing in the row and to decrease lodging. Brown and Lovett (1938) stated that corn grown on ridges, a common practice in southern Louisiana, invariably outyielded corn grown on level plots.

In the 1930's, ridge cultivation of corn was common in southern Illinois. Arguments were often heard against ridging. It was claimed that ridging increased the evaporation of moisture from the soil, but farmers continued to practice ridge cultivation. Dungan (unpublished) conducted experiments over a period of five years to get some data on the reasons for the practice. The difference in yield of grain was negligible, being only 8/10

of a bushel in favor of ridging over level cultivation. In one of the five years level culture gave a slightly higher yield than ridge culture. The largest difference was in standing ability. Less than half as many plants were lodged on the ridged plots as on the level plots. With present-day lodging resistant hybrids, however, ridging to gain standability is no longer necessary.

E. Wide-Row Spacing Versus Conventional Spacing

Many experiments have been conducted with rows spaced wider than 40 inches. One of the earliest of these was by Cunningham (1914) who found that under extremely dry conditions corn rows spaced 7 feet apart produced 16 bushels of grain per acre while rows 3.5 feet apart failed to produce grain. He explained that competition between the roots of close growing plants in wide rows begins earlier than in narrow rows. This tends to check top growth and thus reduces the transpiration surface. The reduction in demand for water enabled the plants to tide over the moisture-critical period and thus maintain a fairly good condition for earing and filling.

In contrast to the favorable report for wide-row spacing by Cunningham, Zook and Burr (1923) in western Nebraska found little difference in grain yield between rows spaced 7 and 3.5 feet apart. Even more at variance with Cunningham's findings were the results of Brandon (1937) in Colorado and Conner (1918) in Texas. These authors found that under the semi-arid conditions of their areas, corn in double-width rows yielded less than that in single-width rows.

Many other workers (Kisselbach *et al.*, 1935; McClelland, 1928b, 1940; Mooers, 1920; and Osborne, 1925) investigated wide-row spacing in areas of more favorable rainfall and reported that 7-foot rows yielded from 15 to 25 per cent less than 3.5-foot rows at the same population level. Yield decreases were even greater when the wide rows had fewer plants per acre. Osborne (1925) and Stringfield and Thatcher (1951) found that in favorable corn-growing seasons, yields produced by the wide-row corn were closer on a percentage basis to yields produced by the narrow-row corn than under poor growing conditions. Different results were reported by Larson and Willis (1957). These workers obtained equal yields for 40-, 60- and 80-inch spaced corn rows. These results were obtained in the drier than normal seasons of 1954 and 1955.

Mooers (1927, 1930) and McClelland (1928b, 1940) used wide-row corn as a means of establishing legume crops. For the most part, their objective was to supplement the corn crop with soybeans or cowpeas for "hogging off" purposes. In recent wide-row corn experiments, Stringfield and Thatcher (1951) used wide-row corn for interseeding wheat in the

fall and suggested that wide-row corn might be used as a nurse crop for the establishment of a forage crop. This latter possibility is very attractive to Midwest farmers who would like to eliminate the relatively low-profit oat crop and still establish a legume crop for hay and pasture. The other highly desirable advantage of a successful seeding in corn would be a winter cover crop to reduce soil erosion and provide organic matter to the soil.

Incidental to studies on the establishment of legumes in corn, several recent trials have compared the performance of the corn in 40-inch rows with that in 80-inch rows. The following workers found the yield reductions to be: Schaller and Larson (1955), 22 per cent; Peterson (1955), 20 per cent; Pendleton *et al.* (1957), 20 per cent; Tesar (1957), 13 per cent. When comparisons of 40- and 60-inch rows were made, considerably less reduction in yield was found by Stringfield and Thatcher (1951), Pendleton *et al.* (1957), and Tesar (1957). In certain trials, alternate 40- and 80-inch row spacings have been compared to uniformly 40-inch row spacings. Stivers (1956) reported a 5 per cent reduction, Pendleton *et al.* (1957), a 10 per cent reduction, and Schaller and Larson (1955) found the reduction to vary with location but to average approximately 10 per cent.

When wide rows were used, it was found important to keep the plant population per acre comparable to that in regular 40-inch row spacings. Pendleton *et al.* (1957) found 80-inch rows yielded much higher at a 12,000 plant population than at a 9,000 or 6,000 population per acre. Haynes and Sayre (1956) found highest yields were obtained in wide rows when the average ear weight was 0.5 lb. In order to have the same plant population in 80-inch rows as in 40-inch rows, the plant spacing within the 80-inch rows is often extremely close and there exists considerable inter-plant competition. Haynes and Sayre (1956) found that the individual plant compensates for this by developing an oblong root pattern perpendicular to the corn row. Plants spaced one inch apart in wide rows had the longest roots perpendicular to the row.

Wide-row corn has provided more success with a legume interseeding than 40-inch rows. The chances of a legume interseeding being successful in wide-row corn depends on a number of factors: time of seeding, rainfall, soil fertility, type of seeding machinery used, and other management practices. In general, earlier legume seeding will produce a better legume stand. However, the early seeded legume offers more competition to the corn crop. Kurtz *et al.* (1952) found that under conditions of high nitrogen and abundant water high corn yields may be obtained when corn is planted in slits of established legumes and grasses. Pendleton *et al.* (1957) obtained excellent stands of alfalfa from seedings made the same day

corn was planted. When the alfalfa was clipped and a 20-inch clean cultivated strip was maintained over the row, corn yields were only 20 per cent below the corn yields on adjacent clean-cultivated areas. Schaller and Larson (1955) suggested that corn should be planted early, cultivated twice, and the legume interseeded as early as possible in June. Johnson (1955) has reported that machinery is available for seeding wide row corn. Jackobs and Gossett (1956) suggested the use of a cultipacker seeder for seeding directly over the corn after the first cultivation, when the corn plants are only 12 to 18 inches tall. One disadvantage in early seeding is the necessity to clip the alfalfa for weed control.

Midsummer legume seedings thrive better between corn rows running in a north-south direction than in an east-west direction (Schaller and Larson, 1955; Pendleton *et al.*, 1957; Larson and Willis, 1957). Thus far, even with the best of practices, legume seedings made in midsummer in wide-row corn have not been consistently successful because of the rainfall factor. Interseeding corn with a leguminous crop remains a tremendously challenging agronomic problem. In contemplating such a practice, a grower must first consider his objectives and decide which crop to favor, the corn or the legume. If the objective is to use corn as a substitute for oats in establishment of a pasture for the following year, then it appears that an early seeding date for the legume is almost a necessity.

VIII. Other Factors Affecting Optimum Plant Population

Before the final answer to the rate of planting question can be given, a few matters other than soil fertility and available moisture supply must be considered.

A. Length of Season Requirement

Length of season requirement is a factor affecting the optimum rate of planting for maximum yields. Most investigators agree that early-maturing varieties can be planted thicker than late-maturing corn. Richey (1933) stated that the rank-growing, long-season varieties of the southern states will not tolerate nearly as thick planting as the smaller varieties of the North. Genter (unpublished) in a three-year test at Holland, Virginia, found that an early hybrid gave its maximum grain yield at 22,000 plants per acre; an intermediate hybrid reached its maximum at 17,600 plants per acre; and a late hybrid gave its highest yield at a population of approximately 13,700 plants per acre. Rossman (1955) of Michigan found that there was a slight tendency for the earlier hybrids to make a greater response than the later hybrids to rate of planting. Dungan (unpublished) found that an early maturing hybrid adapted to Wisconsin, when grown

at different population rates in central Illinois, gave its maximum yield of grain at the same number of plants per acre as U.S. 13, an adapted hybrid. These tests were made with hill-planted corn in rows 40 inches apart. It is believed that if the interval between hills had been reduced as the population was increased, the comparative response of the early-maturing hybrid might have been different. Rounds *et al.* (1951), from tests in Michigan, observed that there was no consistent trend for the early hybrid to give a higher response than the later maturing hybrid to rate of planting.

B. Kind of Corn

Some strains and hybrids possess an inherent capacity to perform better than others under the stress of high population rates. Stringfield and Thatcher (1947) found that hybrids in general will require about 2,000 more plants per acre than open-pollinated varieties to reach the point of highest yield per acre. McVickar and Shear (1946) noted that the hybrid corn with which they worked increased in yield when the population was increased from 3 to 4 plants per hill, whereas the yield of the open-pollinated varieties decreased. Hybrids differ with respect to their response to population levels. Lang (1956) reported that the single-cross hybrid, Hy2 × Oh7, proved highly tolerant to high rates of planting and made its highest yield at 20,000 plants per acre. Single-cross, WF9 × C103, on the other hand, was less tolerant and made its highest average yield at 12,000 plants per acre. Stepping the population up to 24,000 plants per acre reduced the yield of the less tolerant hybrid 32 per cent, whereas it reduced the yield of the tolerant hybrid only 10 per cent. In general, hybrids which showed a tendency to be multiple-eared at low population rates responded the best to high rates of planting.

C. Dwarf Hybrids

Mooers (1910) presented the general proposition that the taller the variety, the less will be the number of stalks per acre which will produce the greatest yield of grain. With the advent of short hybrids, corn growers saw at once the possibility of increasing the population of corn plants per acre and thereby augmenting grain yields over the full-length hybrids. Theoretically, this practice has much in its favor.

In the absence of experimental results on the response of dwarf hybrids to high population levels, only incidental observations are available to answer the question. Corn breeders report that the plants of dwarf corn grouped in a hill appear to compete more acutely with each other than do normal hybrids. This is indicated by the presence of one or more distinctly under-sized plants in the hill. Drilling in the row and narrowing the rows

to bring about a more uniform plant distribution might solve the competition problem. Incomplete filling of cobs on dwarf hybrids in heavy stands has been observed. Vacant space at the butt of ears has also been noted. It is not known whether this is caused by the heavy compact foliage interfering with pollen-silk contact or is due to some internal cause.

The major advantage of dwarf hybrid corn lies in its great lodging resistance. As research with this new type of corn continues, other important advantages, including a favorable response to thick planting, may be discovered.

D. Time of Planting

The time of planting plays a minor role in determining the optimum planting rate. In general, with crops such as corn which tiller relatively little, thin planting tends to slightly hasten plant development. Medium-late planting of corn has been observed to result in plants of greater height. Early planting of seed of the same hybrid results in plants of lesser height. Martin *et al.* (1929) have reported the same experience with sorghum. Late planting tends to increase somewhat the incidence of lodging. These considerations, though not highly important, suggest that corn planted on an early date for the locality may be planted at a slightly thicker rate than at a medium-late or a late date.

E. Purpose for Which the Crop Is Grown

The purpose for which the crop is grown has some bearing on optimum rate of planting. The most important product of the corn crop is grain, and the question of plant population has been presented from the standpoint of maximum grain production. Some growers are interested in the total crop for use as fodder or silage. Experience of growers, generally, is that a rate of planting somewhat above that which gives the maximum grain yield will produce the greatest tonnage of dry matter per acre. Nevens and Dungan (1942), however, pointed out that good silage corn must contain a high proportion of ears. This places such a limitation on the grower of corn silage that he dare not step up the planting rate much above that which under his conditions will produce the maximum yield of grain.

The producer of seed corn has a special objective in the growing of corn. Normally, he is interested in producing as many bushels of shelled corn as he can, but if the highest yield per acre is not the same as the largest amount of high quality seed, he needs to adjust his production program. Dungan *et al.* (1938) reported that the size of kernel was reduced by increasing plant population. General observation and extensive data at the Illinois Station show that the small ears on thick plants have a larger

proportion of round, odd-shaped kernels than the ears produced on medium stands. A wise seed producer will keep this in mind in deciding how thick to plant his ear-parent rows.

IX. Formulas for Determining the Correct Plant Population

Rate of planting has to be decided in advance of knowledge about the growing season. Information as to what the field will produce under average conditions must be used as a guide in solving the problem. Weight of ear on an individual plant basis is a good index as to the correctness of the population. Under central corn belt conditions, 0.5 lb. of ear corn per plant is the approximate amount to aim at. North of this area, ear weight per plant for maximum acre yield will be less and to the south it will be greater. The grower should plant to obtain a population which will do this. The population which produces the smallest amount of ear corn per plant without reducing the per acre yield will give the greatest yield.

With optimum ear weight per plant estimated at 0.5 lb., and if plants are established by 89.3 per cent of the kernels planted, 3,920 seeds will produce 3,500 plants or 1,750 lb. of ears. At 70 lb. per bushel this equals 25 bushels. Since in an acre there are 3,920 hills, 40 inches apart each way, planting one kernel per hill will provide a population which will produce 25 bushels per acre. This constitutes the basis from which the population for higher anticipated yields can be calculated as follows: 2 kernels per hill for an expected 50 bushels; 3 kernels for 75 bushels; 4 kernels for 100 bushels; and so on to even higher levels of production. The equivalent in drilled or hill-dropped corn can be used with equal accuracy.

Miles (1951) in Indiana gave a similar rule for determining the rate of planting most varieties in 38-, 40-, and 42-inch rows. The grower should plant one kernel per hill for each 25 bushels of anticipated yield per acre. With early maturing corn, the grower should plant one kernel per hill for each 20 bushels of expected yield.

Long (1955) in Tennessee stated that a good rule of thumb to follow in determining how thick to plant corn is to allow 100 plants for each bushel of expected yield. For example, 6,000 plants per acre should be provided for a 60 bushel per acre yield and 10,000 plants for a 100 bushel per acre yield. In experimental plots having yields less than 20 bushels per acre, 3,000 plants per acre gave the best results. These rules are based upon the assumption that each plant will produce 0.7 lb. of ears, or 0.56 lb. of shelled grain.

Mooers (1920) presented a formula for ascertaining the optimum planting rate for open-pollinated corn in Tennessee. It is $56\ Y/F = N$, where 56

is the weight of a bushel of shelled corn, Y represents the expected production in bushels per acre under average seasonal conditions, F the average weight of shelled corn per plant at the optimum rate of planting for the highest acre yield, and N the number of stalks per acre. If it is assumed for purposes of illustration that (1) the productivity of the field is 100 bushels per acre and (2) the weight of shelled corn from 0.5 lb. of ears is 0.35, the equation becomes: $56 \times 100/0.35 = 16{,}000$.

X. Discussion

Although many experiments have been conducted to determine how thick to plant corn, the question is not fully answered. Because of the nature of the problem, it perhaps can never be answered once and for all. Each growing season is different from all that have preceded it; the productivity of the land is undergoing constant change; and the inherent make-up of the current hybrids is undergoing modification. This does not mean that selection of rate of planting is a hopeless riddle or that population is not an important matter. On the contrary, it is intensely important and if the corn grower applies all the information he can gain on the subject and makes full use of his experience and judgment, he can make real strides in increasing the grain-yielding efficiency of his fields.

Growers contemplating the problem would do well to bear in mind that it is better to underplant than overplant. An examination of the data presented by Lang *et al.* (1956) on 9 single-cross hybrids indicates that this is the case. The average of all the tests, when the population was down 4,000 plants per acre below optimum, show the yield at 97 per cent of the maximum. When the average was up 4,000 plants per acre, the yield was only 90 per cent of the maximum. Out of all 27 comparisons, 17 showed that the yield of the population just under the optimum was closest to the top yield. Only 10 showed that the yield from the population just over the optimum was closest to the top yield. These results suggest that caution in the matter of thick planting should be exercised.

In many of the earlier fertility experiments, the benefit of soil treatments was measured by determining the yield from plants growing at the same population per acre as the check plot. Normally, in an experiment it is advisable to maintain all conditions constant except the particular factor that is being studied. This rule, however, does not apply to the corn plant population on soil fertility and irrigation plots. The population should be adjusted up or down so that grain-producing efficiency will be at the highest point on an acre basis. This principle applies also in evaluating the performance of hybrids. The entries should be grown at the

population rate which, under the conditions of the test, represents the optimum. This presupposes preliminary tests to discover what is the optimum rate of planting for each hybrid.

Speculations have arisen as to what limits corn yields under extremely high population levels and in soils having abundant supplies of plant food and moisture. Shading of blades by overlapping foliage is believed to be a factor. Lower leaves in a dense stand of corn are exposed to conditions as in a deep forest. Photosynthesis of carbohydrates and other compounds is probably greatly reduced.

Is it possible that solar energy stored in certain types of organic matter, namely nitrogenous types, can be released to the plant partially to make up for that which cannot be secured from the sun? If so, a new approach can be made toward securing high yields by increasing populations. Some evidence supports the idea. Only a few years ago agronomists in the Midwest working in cooperation with the *Farm Journal* and the Schock Bros. Fertilizer and Feed Company set up acre plots to produce high yields of corn. Purely mathematic techniques were used in determining requirements. Thirty thousand plants were deemed necessary to make three hundred bushels. Adequate water and nutrients were added to support the populations. The story was one of complete failure. Only one of 6 areas produced over 100 bushels per acre and that was only 108. In contrast to this Ratliff (1955) in Mississippi produced 304 bushels per acre one year and an exceedingly high average yield of corn for several years. A high population and heavy applications of animal manures thoroughly mixed in the surfaced soil gave these results. Adequate chemicals were incorporated into the soil to cause rapid decay of the organic matter during the growing period of the corn plants. High production in various acre-yield contests of the states almost invariably follows the plowing down of large amounts of manure or nitrogenous organic matter. This fact is so common and seemingly so unimportant that it is scarcely ever publicized.

This past year we were able to produce more than 200 bushels of corn per acre in outside rows of corn with a technique unique in corn growing. Normal fertilizer treatment for high yield was employed. In addition 30 tons of manure were applied and mixed thoroughly with the soil. In the field corn was alternated with soybeans. Strips of 4 rows of corn and 4 rows of soybeans were planted. Corn and bean rows were spaced 24 inches apart. In the row, hills were spaced 24 inches apart with 2 plants per hill. The hills were staggered in the row so as to give more root room per hill. This planting technique gave a population in each row equivalent to 21,780 plants an acre. By the alternating of corn and beans and by staggering the hills it was apparent that considerable competition was eliminated. Even at this thick planting rate per row the ears averaged almost a pound

to the plant. The results make it appear that by this or similar techniques, present yield barriers can be broken. Very high populations with adequate plant food including large quantities of organic matter and water are required.

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LIMING

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I. Introduction

Views concerning many soil characteristics of importance in problems involving soil acidity and liming have changed radically in the past few years. Mehlich and Coleman (1952), in a review of the mineral nutrition of plants as related to the exchange characteristics of soils, cited the then prevalent opinions on such subjects as the nature of soil acidity, the significance of percentage base saturation, and effective concentrations of ions in soil systems. Re-examination of these and other subject matter areas

since this time has necessitated extensive revisions of many ideas and concepts.

The change in opinion on the matter of exchangeable aluminum in acid soils and clays is an excellent example of the results of such re-examination. Though Paver and Marshall (1934) had indicated that aluminum-saturation of such materials might be the rule rather than the exception, it was not until recently that this was generally accepted, at least in this country.

A second area which requires revision concerns cation exchange capacity and percentage base saturation. No astonishing new findings have been made in this field, but interpretations of exchange capacity in terms of source of charge and its implications are providing a more realistic approach to the study of soil acidity and liming. Finally, the great advances which are being made in the mineral nutrition and biochemistry of plants provide the basis for more fundamental understanding of the relations between soil properties and the growth and composition of crops.

The first part of this article is a general and descriptive development of what is believed to be a realistic picture of the ion exchange characteristics. This approach, although somewhat inappropriate for a review article, was taken because the subject is not covered completely in literature which is available currently. The remaining parts of the paper review recent and pertinent information on fundamentals and practices relating to liming, with emphasis on the former.

II. Principles Relating to Liming Soils

A. Soil Factors

1. *Exchange Capacity, Source of Charge, and Ion Saturation*

Because they possess negative charges, soils and soil constituents such as clay minerals and organic matter have the property of binding and exchanging cations. The ion exchange materials in soils differ from one another in the source and magnitude of charge. This has important implications with regard to soil ion exchange characteristics.

The negative charges of soil materials fall into two general categories. The division is conveniently made on the nature of the interaction between such materials and the hydrogen ion. One category interacts largely electrostatically with the hydrogen ion, while the other interacts covalently. The former is typified by the permanent charges of clay minerals, presumably resulting from isomorphous substitution. The most straightforward example of the latter is the charge on soil organic matter, which contains carboxyl and other acid groups (Broadbent and Bradford, 1952) capable

of ionizing to produce positively charged hydrogen ions and negatively charged spots on a solid matrix.

It is important to distinguish between the above considerations and the rather loose statements which have been made concerning the "strong acid" or "weak acid" character of soil colloids. Though there is some overlapping of basic ideas, the emphasis here is on specific kinds of exchange spots rather than on the character of species of clay minerals. In fact, all clays appear to possess or develop both kinds of negative charge, and the usual designation of strong or weak acid depends on the relative amounts of the two.

Probably the most significant single experiment which can be performed on an acid soil is to leach with a neutral salt solution, such as 1 *N* KCl or NaCl. The principal result of such treatment is the displacement of cations which are bonded electrostatically to soil surfaces. Of course, other changes occur as well. These include effects on the ionization characteristics of weak acid groups, changes in the interplanar spacings of 3-layer minerals, with possible fixation or release of certain ions, and the concomitant adsorption of anions and cations by some soils. The latter effects are minor with most soils, and the major result is the displacement of electrostatically bonded ions.

The ions displaced in major amounts on neutral salt leaching of acid soils are calcium, magnesium, aluminum, potassium, and hydrogen. The first three account for 90 per cent or more of the total replacement, the proportions of calcium and magnesium being large in slightly acid soils, while that of aluminum is of major importance in many strongly acid soils. Appreciable quantities of hydrogen ion are not displaced by neutral salts from even quite acid soils, and electrostatically bonded hydrogen ordinarily does not exist in important amounts in soils.

The data shown in Table I illustrate the kind of information obtained by supplementing exchangeable cation and cation exchange capacity (CEC) determinations with neutral salt leaching. The numbers in the column headed Al are the quantities of exchangeable aluminum displaced by 1 *N* KCl. The amounts are negligibly small for the soils with pH near 6, are around 1–2 me per 100 g. for the acid red-yellow podzolic soils, and are large in the case of the Granville, Mayodan and White Store soils, which were derived from Triassic sediments. Only about 6 per cent of the "exchangeable hydrogen" (pH 8.2) of acid-washed peat was exchanged upon leaching with 1 *N* KCl.

In most cases, the sum of the ions displaced by exhaustively leaching an acid soil with a neutral salt solution may be regarded as nearly equal to the permanent charge component of cation exchange capacity. That is,

TABLE I

Cations Replaced from B Horizons of Several Southeastern Piedmont Soils upon Leaching with 1 N KCl

Soil	pH	Exchangeable cations, me per 100 g.					Per cent saturation	
		Al	ΣCa, Mg, K	ΣM⁺	H	CEC	I	II
Granville	4.8	12.1	1.3	13.4	5.7	19.1	9.7	6.8
Mayodan	4.9	8.9	1.8	10.7	4.3	16.0	15.4	11.2
White Store	4.6	17.9	4.5	22.4	7.3	29.7	20.0	15.1
Iredell	6.3	0.4	15.8	16.2	7.5	23.7	97.5	68.3
Mecklenburg	5.8	0.8	9.0	9.8	8.3	18.1	92.0	49.7
Davidson	5.9	0.2	4.5	4.7	7.6	12.3	95.8	36.6
Cecil	5.6	0.8	1.7	2.5	5.0	7.5	68.0	22.6
Georgeville	5.3	2.0	1.5	3.5	6.7	10.2	42.9	14.7
Appling	5.2	1.6	1.1	2.7	4.2	6.9	40.7	16.0
H-Peat	4.1	5.0[a]	0	—	89.0	94.0	—	—
Ca-H-Peat	5.4	1.2[a]	46.3	—	47.7	94.0	—	—

[a] For H-Peat and Ca-H-Peat, the exchange acidity values do not represent exchangeable Al, but H-ions displaced by KCl.

they are the cations neutralizing the negative charges which exist under acid conditions (Schofield, 1949). The column in Table I headed ΣM^+ gives the sums for the several soils. Permanent charge is small for the red-yellow podzolic soils (Cecil, Georgeville, Appling, Davidson), but is considerably larger for the planosols listed first in Table I. Organic matter, as typified by the peat sample, has essentially no charge at low pH.

It may seem radical to speak of permanent charges existing in soils such as the Cecil and Davidson, generally thought to contain kaolin clays. However, there are two reasons why it is proper for such soils to behave in ion exchange as is shown in Table I. The first is that kaolin clays do appear to possess permanent negative charges. Robertson *et al.* (1954) on the basis of chemical analysis, and Schofield and Samson (1953, 1954) from measured negative charges, have shown this to be true. Work in the author's laboratory with a number of mineralogical specimens of kaolinite and halloysite, as well as with soil clays, indicates that kaolins behave as though they have between 2 and 10 me per 100 g. of permanent charge.

A second reason why red-yellow podzolic soils should have permanent charges is that many, if not most, contain 3-layer clay minerals, perhaps a variety of vermiculite. The proportions of such minerals generally increase

with depth, with the result that the permanent charge components of CEC may be very large in lower horizons.

The permanent charge on mineral particles is not the only contributor to the capacity of soils to bind cations. All soils are buffered above pH 6, presumably because of the development of negative charges of weak acid character as the pH is raised. Schofield (1949) has regarded the ionization of SiOH groups as responsible for the development of this pH-dependent charge by clays. Others have suggested that shifts in the coordination number of aluminum in clay lattices from 6 to 4 may be the cause (Goates *et al.*, 1956). It also has been supposed that permutite-like aluminosilicates containing aluminum ions in 3-coordination may act as Lewis acids, accepting electrons from water molecules, with the subsequent ionization of one hydrogen from the chemisorbed H_2O (Tamele, 1950; Mapes and Eischens, 1954).

The above possibilities apply particularly to crystalline clays. Many soils contain more or less amorphous aluminum and iron silicates or phosphates which may contribute to cation exchange capacity under some conditions. Alophane, for example, has been found to be a prominent constituent of some soils (Birrell and Fieldes, 1952; Tamura *et al.*, 1955). The pH-charge characteristics of such substances are not known, but it seems probable that most of their base-binding capacity is of the pH-dependent type.

The column labeled H in Table I shows the negative charges which developed when KCl-leached soils were treated with Mehlich's $BaCl_2$-triethanolamine (TEA) solution buffered at pH 8.2 (Mehlich, 1942). Actually these are values for the "exchangeable hydrogen" in salt-leached soils, and reflect the quantities of weak acid functional groups which become operative as base-binders at pH 8.2.

The magnitudes of the pH-dependent charges are quite large. For the Davidson soil, which is about 50 per cent clay, the value is 7.6 me per 100 g. On a clay basis this would be around 15, and appears to be much larger than one would expect from the ionization of SiOH structures on the edges of kaolin particles. Clay ($<2\ \mu$) from this particular Davidson soil has a glycerol specific surface of 82 m^2 per g., which would give an edge contribution to CEC of 7 me per 100 g., if one uses Hendricks' (1945) edge: face ratio.

The CEC column in Table I contains the summation of exchangeable metal cations (permanent charge) and exchangeable hydrogen (pH-dependent charge). This is entirely analogous to a $BaCl_2$-TEA cation exchange capacity, or one determined by equilibration with $Ca(OH)_2$ and CO_2. Ammonium acetate (neutral, normal) exchange capacities for the

soils are intermediate between ΣM^+ (permanent charge) and CEC (permanent charge plus weak acid charge developed at pH 8.2). Exchange capacities determined at pH 9 or 10 are correspondingly larger than those measured at pH 8.2, because more pH-dependent charge develops at the more alkaline reactions.

Several points should be made concerning the material discussed above.

1. Permanent charge, which is the sum of exchangeable metal cations, including aluminum, is an important characteristic of acid mineral soils. It varies from about 2 me for some kaolins to over 100 me per 100 g. for many 3-layer clays.

2. Cation exchange capacity as determined in conventional ways measures the permanent charge and a fraction of the pH-dependent charge.

3. "Exchangeable hydrogen," as measured with buffer solutions or by difference between CEC and total calcium, magnesium, potassium, and sodium, is really the sum of exchangeable aluminum and whatever weakly acidic groups ionize in the course of the determination.

4. Percentage base saturation is an exceedingly arbitrary datum, depending as it does on the proportion of the pH-dependent charge included in its calculation. The last two columns in Table I show saturation percentages calculated from permanent charge and from CEC (pH 8.2), respectively. The values calculated from CEC are uniformly lower, very much so for the red-yellow podzolic soils. With the Davidson soil, for example, the percentage base saturation of permanent charge is 94, whereas the corresponding number calculated from CEC is 28. It seems true for all soils that a pH of around 6 corresponds to the saturation of permanent charge with basic cations such as calcium and magnesium. A pH below 5.5 reflects the presence of appreciable amounts of exchangeable aluminum, whereas a pH below 5 is indicative of large aluminum saturation, the actual quantity of exchangeable aluminum depending on the capacity of the soil.

An additional feature of the ion exchange characteristics of kaolin minerals and some soil clays concerns the concomitant adsorption of anions and cations at low pH. Schofield and Samson (1953, 1954) have found that at pH lower than about 4, kaolinite adsorbs chloride ions, and that the net negative charge is reduced by an amount corresponding to the anion sorption. This effect is much more pronounced with certain soil clays, particularly those containing large amounts of free iron oxides (Schofield, 1949).

Schofield and Samson suppose that clays possess both positive and negative charges, the former developing progressively as the pH is low-

ered. In salt-free acid clay-water systems, internal compensation occurs, and the net charge is the algebraic sum of the permanent negative charge and whatever positive charge exists at the prevailing pH. When a salt solution is added, the anion coordinates with positive and the cation with negative spots. Upon washing with water the anions desorb accompanied by cations to maintain electroneutrality. The authors have observed this behavior for a number of red-yellow podzolic soils.

Another factor contributing to negative charge in soils is organic matter. Though more is known about the structural details and compositions of clay minerals than about soil organic matter, the source of cation exchange capacity for the latter perhaps is better understood.

Several kinds of functional groups which can dissociate hydrogen ions exist in all samples of well-decomposed soil organic matter, though their proportions appear to vary from one sample to another. Carboxyl groups occur in amounts between about 100 and 200 me per 100 g. of air-dry material, and afford the major source of charge of significance in liming and plant nutrition problems (Broadbent and Bradford, 1952). So far as the ionization characteristics of the carboxyl groups are concerned, soil organic matter behaves as an insoluble weak acid (Dawson *et al.*, 1951; Chatterjee and Bose, 1952). Its pH-neutralization characteristics can be described by an equation:

$$\mathrm{pH} = \mathrm{pK} + n \log (s/1 - s)$$

where K is the intrinsic ionization constant, n is an integer, usually around 2, and s is the degree of neutralization.

As with all polymeric electrolytes, the magnitude of the ionization constant, K, depends both on the electrolyte content of the system and on the nature of the cations present. For neutralization with hydroxides of alkali metals, pK for soil organic matter is around 5. It is smaller by about 0.5 when $Ca(OH)_2$ is the neutralizing base, and is greatly reduced by high salt contents or by the presence of polyvalent metal ions such as iron, aluminum, or copper, which appear to be complexed strongly by the functional groups of organic matter.

Other acid groups of soil organic matter include phenolic and enolic hydroxyls and perhaps imide groups. These appear to be much weaker acids than do carboxyls and do not ionize appreciably at pH below neutrality (Broadbent and Bradford, 1952). Just as for the carboxyls, the numbers of the more weakly acidic functional groups per unit weight of soil organic matter vary from one sample of material to another. Their estimation by titration is most uncertain, since one is not sure when all carboxyls have been neutralized and at what pH ionization of weaker acid groups begins. In addition, organic matter undergoes alkaline oxida-

tion, so that titration to high pH does not yield straightforward results. Probably the best estimates of the proportions of carboxyl and other acid groups in soil organic matter have come from methylation experiments, such as those of Broadbent and Bradford (1952).

The result of the occurrence of various weakly acidic functional groups in soil organic matter is that the degree of ionization and the effective cation exchange capacity varies in a characteristic way with pH. Thus for a sample with a carboxyl ($pK \approx 5$) content corresponding to 150 me per 100 g. and with 150 me of acidic hydroxyls, the potential cation exchange capacity is 300 me per 100 g., but the effective CEC, available for binding metal cations, will vary between this maximum and zero, depending on the environment of the sample. At pH 5 ($pH = pK$, carboxyl groups one-half neutralized), the effective CEC is 75 me per 100 g. At pH 7, it is around 150 me per 100 g., while at pH 4 the effective CEC is only 25. Only at alkaline reactions will exchange capacity contributions from hydroxyl groups result, and the latter are of little significance so far as the exchange characteristics of acid soils are concerned.

The weak acid groups of soil organic matter form relatively stable complexes with polyvalent cations (Beckwith, 1955; Broadbent, 1957; Broadbent and Ott, 1957; Coleman *et al.*, 1956). According to Broadbent and Ott (1957), carboxyl groups are largely responsible for the binding of calcium and magnesium, complexes of these ions being rather weak. The relatively unstable binding of calcium and magnesium, along with the large affinity of hydrogen ions for weakly acidic spots, make for ready replaceability of these ions from organic matter by acids. That is, compared with hydrogen, calcium and magnesium appear to be bound weakly. On the other hand, because calcium and magnesium are complexed to some extent, their affinity for organic matter is much greater than that of alkali metal or ammonium ions. Von Schactschabel (1940) found a Ca-adsorbed: NH_4-adsorbed ratio of 92:8 on leaching "humic acid" with an equinormal mixture of calcium acetate and ammonium acetate. Comparable ratios for montmorillonite and kaolinite were 63:37 and 54:46, respectively.

2. *Effective Concentrations of Calcium and Magnesium in Soils*

In considering the mineral nutrition of plants growing in soils, the ion populations of the exchange spots and the relations between these and ion concentrations in soil solutions are of great importance. Formulations of rules relating to the distributions of ions between adsorbed and solution states may be classified in several categories. They include double-layer theory, Donnan distribution considerations, kinetic and statistical ap-

proaches, and applications of thermodynamics. Considering ion exchange reactions of the sort:

$$y\, A^{x}{}_{sol} + x\, B^{y}{}_{ad} \rightleftarrows x\, B^{y}{}_{sol} + y\, A^{x}{}_{ad}$$

one can write the equilibrium expression:

$$k = \frac{[B^{y}{}_{sol}]^{x}[A^{x}{}_{ad}]^{y}}{[A^{x}{}_{sol}]^{y}[B^{y}{}_{ad}]^{x}} \tag{1}$$

The brackets denote activities, the subscripts "sol" and "ad" refer to solution and solid phase ions, respectively, and k is the exchange constant.

As long as Eq. (1) contains activities of soil solution ions and exchangeable ions, properly defined in terms of electrochemical potential, k equals unity. This approach does not lead to useful information about ion distributions.

Wicklander (1955) regards the distributions of ions in soil systems as best described as Donnan equilibria. It is his view that for exchange of ions of equal valence, insertion of concentrations of exchangeable ions and activities of solution phase ions into Eq. (1) yields a number which is the ratio of the activity coefficients of the two ion species. For exchange between ions of different valence, the ion product is the ratio of activity coefficients taken to appropriate powers multiplied by the volume of the "micellar" solution (that occupied by the exchangeable ions), the latter to some power as dictated by the valences of the exchanging ions. In regarding ion exchange as a Donnan equilibrium, one is confronted with quantities which have not been measured and which at present seem not to be measurable. It is a view which cannot be proven to be wrong; neither can it be proven correct. Although the Donnan equilibrium concept of ion exchange, as supported by Wicklander, provides an excellent qualitative way for visualizing shifts in ion exchange equilibria, as on dilution or concentration of the soil solution, it is not useful in the quantitative sense.

Kerr (1928) regarded Eq. (1) as being analogous to a mass action expression for a double decomposition reaction, with activities of exchangeable ions proportional to their concentrations (see Eq. 2). Vanselow (1932) preferred to treat the activities of the exchangeable ions as proportional to their mole fraction rather than to their concentration (Eq. 3), an approach which also was favored at one time by chemists studying ion exchange with synthetic resins (Boyd *et al.*, 1950). Krishnamoorthy and Overstreet (1949) derived a "statistical" exchange equation (Eq. 4) which, for practical purposes, is much like that of Vanselow. The three formulations of ion exchange equilibria may be illustrated as follows, using K-Ca exchange as an example:

$$k = \left[\frac{(\text{Ca ad})\cdot(\text{K sol})^2}{(\text{K ad})^2\cdot(\text{Ca sol})}\right] \tag{2}$$

$$\left[\frac{(\text{Ca ad})\cdot(\text{K sol})^2}{(\text{K ad})^2\cdot(\text{Ca sol})}\right]\cdot[(\text{Ca ad}) + (\text{K ad})] \tag{3}$$

$$\left[\frac{(\text{Ca ad})\cdot(\text{K sol})^2}{(\text{K ad})^2\cdot(\text{Ca sol})}\right]\cdot[3/2(\text{Ca ad}) + (\text{K ad})] \tag{4}$$

Krishnamoorthy and Overstreet (1950) found that the latter two formulations described ion exchange equilibria quite satisfactorily for a variety of adsorbents and ion pairs. Others have found somewhat poorer agreement between results and predictions (Harward and Coleman, 1953), but it seems that equations such as (3) and (4) are useful in describing ion distributions.

If one rearranges any of Eqs. (2), (3), or (4), and takes square roots, one obtains, *as long as the ion saturation does not change,*

$$\frac{(\text{K sol})}{\sqrt{(\text{Ca sol})}} = \text{constant} \tag{5}$$

This, of course, is the "ratio law" of Schofield, although Schofield and Taylor (1955) derive it in a different way.

Equation (5) is useful in at least two ways. It enables one to visualize easily shifts in ion exchange equilibria on dilution or concentration, since for each 2-fold change in (K sol) a 4-fold change in (Ca sol) is required. It also provides an index to the ionic nature of a soil which is characteristic and which does not vary with such factors as soil-water ratio and electrolyte content.

Krishnamoorthy and Overstreet (1950) also tested the Gapon equation for exchange equilibria between ions of different valence, finding it less satisfactory than either Eqs. (3) or (4). Again for K-Ca exchange, the Gapon equation is:

$$k = \frac{(\text{K sol})\cdot(\text{Ca ad})}{\sqrt{(\text{Ca sol})}\cdot(\text{K ad})} \tag{6}$$

Bolt (1955), from the double-layer theory, deduced a similar expression for the distributions of ions of unequal valence.

Workers at the Salinity Lab at Riverside (Richards, 1954), in studying relations between sodium and calcium concentrations in saturation extracts of soils and quantities of these ions in exchangeable form, have obtained good correlation between

$$\frac{\text{Na}}{\sqrt{\frac{(\text{Ca} + \text{Mg})}{2}}}$$

in solution and the ratio Na ad: (Ca + Mg) ad. Perhaps the Gapon-Bolt exchange equation (6) will find equally successful application in other areas.

An interesting point in connection with the choice of an appropriate ion exchange formulation concerns the possible effect of the cation exchange capacity of an adsorbent on the selectivity for divalent over monovalent ions. Wicklander (1955) contends that the Donnan equilibrium requires greater selective sorption of divalent ions the larger the capacity of the exchanger, and cites results obtained with samples of exchange resin, montmorillonite, illite, and kaolinite as illustrative of this. The exchange capacities (pH 7) of the materials were 250, 81, 16, and 2.3, respectively, whereas the ratios of adsorbed calcium to adsorbed potassium were 36, 22, 8.1, and 5. Similar results were obtained by Krishnamoorthy and Overstreet (1950).

Because the change in capacity involved a change in adsorbents, it is not clear which factor is responsible for the wide variation in ion ratio observed. Wicklander's view that the selectivity of montmorillonite for calcium is greater than that of kaolinite because the former has a more concentrated "micellar solution" is not tenable. For kaolinite, with a surface area of around 20 $m.^2$ per g. and a CEC of 2–3, the surface charge density is nearly the same as that of montmorillonite (800 $m.^2$ per g., 81 me).

If a series of exchangers, varying in capacity, but with the same Ca-K exchange constant, were leached with solutions having the same Ca/K ratios, the Kerr equation (2) would require greater apparent selectivity for Ca with increasing capacity. Each 2-fold change in K ad would be accompanied by a 4-fold change in Ca ad. The Gapon equation (6) on the other hand, does not predict such a capacity-dependent change in the ratios of the exchangeable ions.

Though the study of ion exchange had its beginnings in soil science, recent advances in theory and experiment have come largely from people in chemistry. The literature in this area is extensive, and is summarized yearly in excellent articles in *Annual Review of Physical Chemistry* (Gregor, 1957; Thomas and Frysinger, 1956; Schubert, 1954; Boyd, 1951).

Most of the work outside the field of soils deals with synthetic exchange resins. Many individuals treat ion exchange equilibria with such materials from the Donnan point of view, though their approaches are more sophisticated than those referred to earlier. A great advantage of exchange resins over clays in this regard is that "inside" and "outside" solutions may be defined experimentally.

Gluekhauf and Kitt (1955) have made an elegant study of ion exchange with such materials and have clarified the matter of ion hydration and its

relation to exchange. Earlier papers by Boyd (1951), Gregor (1951), and Boyd and Soldano (1953) also consider ion exchange from the Donnan equilibrium viewpoint. Duncan (1955) and Holm (1956) have dealt extensively with the thermodynamics of ion exchange. Faucher and Thomas (1954) and Gaines and Thomas (1953) worked with clays rather than exchange resins and derived thermodynamic functions to describe ion exchange.

Much fundamental work also has been done with polyelectrolytes such as acrylic and methacrylic acids. These are linear polymers containing carboxyl groups and resembling soil organic matter in their titration and ion exchange behavior. Gregor *et al.* (1956) and Fisher and Kunin (1956) have studied neutralization-pH relations and ion binding in such materials.

In addition to attempts to describe distributions of ions in exchanger systems through the application of equilibrium equations, "activities" or "exchangeabilities" of ions have been sought in other ways.

Bray (1942) conducted fractional exchange experiments by adding small amounts of HCl to soils and obtaining ratios of: % M^+ released/% Ca released. These ratios, called *f*-values, were large for ions such as potassium, but smaller for more strongly bound ions such as magnesium. Using experimentally determined *f*-values and quantities of exchangeable cations, Bray was able to calculate the quantities of each ion which would be released on the addition of electrolyte to a soil.

Mehlich (1946) also conducted fractional exchange experiments, obtaining *f*-values which varied with the extent of the exchange and also with the nature of the soil. In particular, he found the *f*-value for the hydrogen ion to vary tremendously, being <1 for organic soils and for soils containing kaolin clays, and >1 for soils containing montmorillonoids.

Wicklander (1955) also suggests that fractional exchange experiments will provide information concerning the "activities" of exchangeable ions.

Approaches of this kind, though empirical, appear to have considerable application to the study of ion exchange in soils as it relates to plant nutrition. Using this scheme, Mehlich (1946) and Milam and Mehlich (1954) have been able to predict plant contents of cations fairly successfully.

Potentiometric measurements of ion activities in soils with membrane electrodes (Marshall, 1949) or with two-compartment cells (Peech and Scott, 1951) were in great vogue a few years ago. Marshall and his students, in numerous papers, have presented detailed results. Marshall (1949) and Mehlich and Coleman (1952) summarized some main findings, which are in general agreement with the results of fractional exchange experiments.

As discussed in another section, the weight of present evidence is to the effect that potentiometric measurements on colloidal systems, using

cells with liquid junctions, are subject to errors which usually are difficult to determine. Consequently, the numerical values which have been obtained for ion activities are suspect, though many of the general patterns which have been established are valid and useful.

3. *Soil pH*

The interpretation of potentiometrically measured pH of soil suspensions has been the subject of much investigation and controversy in recent years (Jenny *et al.*, 1950; Coleman *et al.*, 1951; Marshall, 1951; Peech and Scott, 1951; Eriksson, 1951; Overbeek, 1953; Peech *et al.*, 1953; Low, 1954). The objective of this section is to discuss the situation in a qualitative way. A deliberate attempt has been made to avoid complicating the presentation through reference to theoretical matters which are considered in detail in the various literature citations.

The observation is commonly made that the pH of a suspension of negatively charged soil particles as measured with the glass electrode-calomel electrode assembly is lower than that of the clear supernatant solution. This phenomenon has been termed the suspension effect (Pallmann, 1930; Wiegner, 1931).

The potentiometric measurement of pH is based on the fact that hydrogen-ion-sensitive electrodes can be constructed which are more or less insensitive to other ions in the system under most conditions. The most commonly used hydrogen-ion-reversible electrode is the glass membrane electrode (Dole, 1941) which is usually paired with the calomel reference electrode. In pure electrolyte solutions it is commonly agreed that unless a junction potential exists at the junction between the KCl salt bridge and the test system, the potential of the cell at constant temperature varies only with the activity of hydrogen ions in the test system. The use of a saturated KCl salt bridge is held to minimize the junction potential and when the test system is a pure solution this potential is considered negligible. Thus the cell emf may be interpreted in terms of the hydrogen ion activity. The introduction of nondiffusible ions of high charge into the test system suggests the possibility of additional potentials being created and interpretation of the cell emf becomes more complex. This is the point of departure in a consideration of the real meaning of a potentiometric measurement of soil pH.

There are two general viewpoints regarding the origin of the suspension effect. One holds that since hydrogen ions accompany the charged particles, the hydrogen ion activity is greater in the suspension phase, as contrasted to the equilibrium solution phase. Thus a lower pH would be expected. The other viewpoint is that the pH of the suspension phase appears lower than that of the solution phase because of a junction potential

where the KCl bridge contacts the charged particles. Thus, the suspension effect does not represent a real difference in pH between the two phases, but is a property of the electrodes used to measure pH. It follows, according to this theory, that increasing suspension concentration results in a lower apparent pH, a phenomenon commonly observed (McGeorge, 1937).

The classic description for the relationship between the suspension and solution phases has been based on the Donnan theory of ion equilibria (Marshall, 1949). The applicability of this theory to clay suspensions has been questioned on the grounds that Donnan theory assumes homogeneous volume charge in the suspension phase (Bolt and Peech, 1953), a condition which, according to Schofield (1947), can never hold in bentonite suspensions.

The second general viewpoint regarding the cause of the suspension effect, that it originates at the junction between the KCl bridge and the suspension, has been approached in several ways. Jenny *et al.* (1950) and Coleman *et al.* (1951) postulated that the mobilities of potassium and chloride ions are drastically altered in the presence of the charged clay particles. The suspension of negatively charged particles thus acts like a leaky (Spiegler *et al.*, 1956) or slowly permeable membrane, inhibiting the transfer of chloride ions and increasing the contribution of potassium ions to the transfer of current. This would give rise to a junction or diffusion potential due to the unequal transfer of cations and anions across the salt bridge-suspension boundary. The extreme in a situation such as this is realized in the case of a completely ion-selective membrane, as represented by the glass electrode and approached by mineral membrane electrodes (Marshall, 1949). In the latter systems anion transfer is negligible or at least small, and thus current transfer is a function of cation activity only. Jenny *et al.* (1950) and Coleman *et al.* (1951) developed an equation based on modified transference numbers of potassium and chloride ions that predicted fairly well the measured membrane potential between suspension and equilibrium solution.

Overbeek (1953) was able to derive the suspension effect from the conditions existing at the two liquid junctions of calomel electrodes used to measure the membrane potential. His approach to the problem was different from the Jenny *et al.* (1950) and Coleman *et al.* (1951) approaches in that he considered the contribution of electro-osmosis to the transfer of current. It is interesting that his equation, based on chemical potentials and transference numbers in the two liquid junctions, reduces to the Coleman *et al.* (1951) equation.

Other workers (Sollner, 1953; Mysels, 1951) have concluded, in line with the foregoing, that junction potentials occurring at the junction of

the salt bridge and the suspension contribute largely to the emf of the cell used to measure membrane potentials.

The most recent contribution to the field is that of Spiegler *et al.* (1956). These workers considered the potential developing across a porous plug of exchange material and constructed an equation based on the difference in conductivity of ions through solution, cation exchanger, and cation exchanger plus solution. The potential thus derived was termed a plug potential. Measurements, utilizing silver-silver chloride electrodes, of the potential developed across a plug of ion exchange material separating solutions of various concentrations of NaCl agreed very well with predicted values.

It is impossible, on the basis of present evidence, to state with certainty the real and complete cause of the suspension effect. The weight of evidence seems to favor the approach based on modified ion mobilities in clay suspensions. Recent work by Lorimer *et al.* (1956) and Gregor and Wetstone (1956) establishes the fact that transport numbers are modified drastically by a charged membrane. Considering a clay suspension as a porous plug or leaky membrane suggests that while the transport number of ions of like charge to the clay may not approach zero, it would be sufficiently modified to create a diffusion or junction potential at the KCl bridge-suspension junction.

It is probable that a significant junction potential is created in the salt bridge whenever a calomel electrode is inserted in a clay suspension. One would conclude that no intrinsic meaning regarding single ion activities can be placed on soil suspension measurements using glass or membrane electrodes in conjunction with the calomel half-cell. This does not, of course, imply that such measurements are of no value. However, their limitations should be realized.

Schofield and Taylor (1955) believe that measuring the pH of dilute $CaCl_2$ solutions in equilibrium with soils has the advantage of eliminating junction potentials, as well as providing measurement of the mean activity of $Ca(OH)_2$.

Measurement of soil pH in relatively concentrated salt solutions, such as 1 N KCl, also eliminates junction potentials. However, in view of the extensive Al-saturation of many acid soils, the pH measured in this way may be more properly regarded as being that of dilute solutions of $AlCl_3$ rather than those of soils.

Soil pH and its relation to equilibria in Ca-soil-water-CO_2 systems have been considered by a number of individuals, among them Simmons (1939), Whitney and Gardner (1943), Bradfield (1941), and Cole (1957). Most of the work has been directed toward the understanding of pH, calcium saturations, and calcium solubilities in calcareous soils. This work also is

pertinent to some extent to the solubility of lime applied to acid soils, in that the immediate vicinity of limestone particles is calcareous on a microscale.

Bradfield (1941) has pointed out that in a soil system containing free $CaCO_3$, the quantity of $Ca(HCO_3)_2$, and consequently the pH and the amount of Ca in solution, depends on the CO_2 partial pressure. Cole (1957) has treated such systems in a most satisfactory way, deriving equations for the mean activity of calcium hydroxide in terms of CO_2 partial pressure, the solubility product of the $CaCO_3$ species present, and the salt concentration.

4. Movement of Lime in Soils and Leaching Losses

The movement of lime through soils from a zone of application and the leaching of calcium and magnesium have been studied in lysimeters (MacIntire, 1926; Lyon and Buckman, 1936), in soil columns (Ririe *et al.*, 1952; Mehlich and Reed, 1945; Blume, 1952), and in field experiments (Brown *et al.*, 1956).

Because the reaction of lime with soils involves neutralization, with little if any soluble anion as an end product, the movement of calcium and magnesium away from the point of reaction is relatively slow, and the calcium and magnesium contents of soil leachates usually are small. However, it is not possible to generalize in this regard, since the quantities of soluble anions in soils vary with fertilization, cropping, and microbiological activities, and since quantities of calcium and magnesium in soil solutions depend on the electrolyte content, the complementary ions, and the nature of the interaction with the exchange materials in the soil.

The last factor is illustrated by the results of Mehlich and Reed (1945), who found the leaching loss of calcium from a Ruston sandy loam (North Carolina coastal plain) to increase rapidly with calcium saturations above about 40 per cent (CEC pH 8.2) and to depend strongly on the salt content of the soil and to a smaller extent on the potassium saturation of the soil.

Ririe *et al.* (1952) added to the top layers of soil columns sufficient quantities of several liming materials to completely neutralize the exchange acidity of the soil in the entire column, and leached with 44 inches of water. Essentially no calcium was leached from a high CEC soil, though about 18 per cent of that applied appeared in the leachate of a sandy soil of low CEC (Sassafras). There was little neutralization of the acidity in soil layers below the zone of lime application. In field experiments, Brown *et al.* (1956) found that heavy applications of limestone applied to surface layers of acid Connecticut soils had raised the pH of

the 19- to 24-inch layer after 9 years, and of the 25- to 30-inch layer after 23 years.

The proportions of the calcium and magnesium leaching from surface layers that will be retained in underlying acid subsoils depend on the exchange characteristics and ion saturation of the soil and the anion accompanying the leaching calcium and magnesium. With aluminum soils, little calcium or magnesium is adsorbed from dilute solutions of neutral salts, such as nitrates, though sorption from bicarbonate solutions is relatively complete. Recently Rible and Davis (1955) and Bower *et al.* (1957) have applied chromatographic theory to the description of leaching processes in soils. Work of this kind, along with a more complete understanding of the interactions between ions and exchange materials, will provide a more general concept of lime leaching.

B. Plant Factors

1. *Functions of Calcium and Magnesium in Plants*

Pirson (1955) has prepared an excellent review on functional aspects in the mineral nutrition of plants. The function of any metal ion can be considered from two points of view. One viewpoint considers effects on specific enzyme reactions in which the ion has an activating or depressing effect. The other viewpoint is less definite and involves the effects of deficiency, sufficiency, or excess of the ion on gross physiological response.

Calcium has not been implicated directly in the activities of many enzyme systems in plants. Though calcium activates both arginine kinase and adenosine triphosphatase (ATPase) from plants (McElroy and Nason, 1954), it is not specific in this regard. On the other hand, calcium strongly inhibits the transphosphorylation from phosphoenolpyruvate to adenosine diphosphate (ADP) (Kachmar and Boyer, 1953; Miller and Evans, 1957). Pirson (1955) suggests that calcium inhibition of potassium-requiring enzymes may be the rule, accounting perhaps for the calcium-potassium "antagonism" observed by so many.

A number of specific physiological effects can be attributed to calcium, but no enzymatic basis is apparent for them. Burstrum (1952, 1954) has found calcium absolutely necessary for the growth of wheat roots. A substrate concentration of 10^{-6} M was required for cell division, but cell enlargement did not occur at concentrations below 10^{-5} M. An anti-auxin character was attributed to calcium. Burstrum (1954) also found an interaction between the effects of calcium level and pH on root growth, more calcium being required at pH 4.5 than at pH 6 to sustain a given rate of root extension.

In addition to influencing the gross enlargement of roots, substrate calcium has large effects on the rates of absorption of other ions. The "Viets effect" (Viets, 1944), originally observed as an acceleration by calcium of potassium uptake by barley roots, has been studied by a large number of individuals. Overstreet *et al.* (1952) and Nielson and Overstreet (1955) confirmed the stimulating effect of calcium on potassium absorption, particularly at low pH. Similar observations were made by Kahn and Hanson (1957) for corn and soybean roots. Tanada (1955, 1956) found substrate calcium (10^{-3} to 10^{-4} M) to increase the uptake of rubidium and phosphate substantially, and Leggett and Epstein (1956) made similar observations for sulfate. Tanada (1956) found that pretreatment of roots with calcium salts is ineffective in increasing ion uptake.

The mechanism through which calcium accomplishes a stimulated absorption of other ions has not been established. Leggett (1956) indicates that an increased turnover of the site involved in HPO_4 absorption can be attributed to calcium. Nielsen and Overstreet (1955) speculated that calcium acted as a cofactor in potassium absorption by increasing the rate of utilization of the potassium-carrier complex.

Florell (1956) has related the substrate calcium level to another root characteristic, the quantity of mitochondria. He found that increasing substrate calcium from 0 to 10 mM increased root mitochondria by 54 per cent and protein by 29 per cent. In a later paper (Florell, 1957) he reiterated the idea that there is a positive relation between calcium nutrition and quantity of root mitochondria, and pointed out the parallelism between this and a calcium-stimulated absorption of nitrate and bromide. Since mitochondria may be involved as ion carriers in the absorption process (Robertson *et al.*, 1955), a causal effect is possible.

Burstrum (1953) has attached considerable significance to relations between the calcium and nitrogen nutrition of plants. As with other ions, calcium stimulates the absorption of nitrate (Burstrum, 1953; Florell, 1957). Gauch (1957) discusses the effects of calcium on nitrogen metabolism, pointing out that minus calcium plants neither absorb nor utilize nitrate effectively. When urea rather than nitrate is supplied, minus calcium plants make more growth and survive longer, but calcium requirements generally are less when ammonium rather than nitrate is the nitrogen source.

Prevot and Ollagnier (1954) have associated aging of plant cells with increasing Ca-K ratios, pointing out that this results in lessening of the hydration of the tissues. Hewett (1953) has found, however, that young root cells with wide Ca-K ratios (K deficiency) do not behave as do aged tissues.

According to Gauch (1957), the idea that calcium pectate is an im-

portant cell wall constituent probably is wrong. He refers to data of Conrad (1926) as indicating that pectic acid is not present in most plant tissues, being found in many assays because of the universal presence of active pectases. Though calcium pectate may not occur in cell walls, calcium appears essential for their proper development (Burstrum, 1954; Gauch, 1957).

Another effect of calcium deficiency appears to be interference with the translocation of carbohydrates (Gauch, 1957). For example, Joham (1957) found carbohydrates to accumulate in the leaves of calcium-deficient cotton plants.

Magnesium is an important activator for many of the enzymes involved in glycolysis and respiration (McElroy and Nason, 1954). Reactions involving group transfers generally have magnesium requirements. Among these are the kinases, which accomplish the phosphorylation of carbohydrates and other such compounds (sugar + ATP $\xrightarrow[\text{kinase}]{\text{Mg}}$ sugar phosphate + ADP). Magnesium also activates many enzymes in the citric acid cycle, including carboxylases, oxidases, and dehydrogenases.

Since magnesium is involved in most, if not all, phosphate transfer reactions, it is not surprising that relations between the magnesium level of the substrate and the phosphate nutrition of plants have been observed (Wallace and Ashcroft, 1956). Mazelis and Stumpf (1955) have found that magnesium is required for the esterification of inorganic phosphate into ATP, which probably is the first step in the incorporation of phosphate into plant metabolism. This provides a direct link between magnesium and phosphorus. Also, Mazelis and Stumpf (1955) have provided a more satisfactory explanation for magnesium-phosphorus relations in place of the rather vague ideas that magnesium may be a "carrier" for phosphate in plants.

Pirson (1955) has discussed the role of magnesium in photosynthesis. Apparently chlorophyll and catalase have a common metal-free precursor, the latter being formed at the expense of the former in magnesium-deficient algae and higher plants (Finkle and Appleman, 1953; Appleman, 1952). However, lack of magnesium inhibits photosynthesis more than it inhibits chlorophyll formation (Fleischer, 1935), perhaps because of the disturbance of phosphate transfers.

Magnesium deficiency leads to reduced protein synthesis (McElroy and Nason, 1954; Pirson, 1955). The latter points out that magnesium complexes strongly with sulfhydryl groups, and may inhibit some enzyme systems.

The work of Miller and Evans (1957) points up the interesting situa-

tion in which a magnesium-requiring enzyme (pyruvic kinase) is strongly inhibited by calcium. They suggest that Mg-ADP may be necessary as a cofactor, and that competition from Ca-ADP for active enzyme sites can decrease the reaction rate.

2. *Ion Absorption by Plants*

Although a detailed discussion of ion uptake and transport is not appropriate in this paper, consideration of a few pertinent points seems in order. It appears that ions may enter roots by diffusion, through exchange adsorption, and by the action of carriers or ion-binding compounds. In this regard, root volume may be divided into two components. One component is the outer space or apparent free space, occupied by solution at equilibrium with the ambient medium. The other component is inner space, probably vacuolar. In contrast to the outer space, where diffusion and exchange adsorption govern ion populations, ions are absorbed metabolically, selectively, and more or less permanently into the inner space.

According to Gauch (1957), the modes of entry into the two "spaces" may be summarized as shown in Table II.

TABLE II

Outer	Inner
Diffusion and exchange adsorption	Ion-binding compounds or carriers
Nonlinear with time, equilibrium approached in short times	Linear with time
Ions stoichiometrically exchangeable for other ions	Ions essentially nonexchangeable and dialyzable
Not highly selective	Specific with regard to site and entry
Nonmetabolic	Dependent on aerobic metabolism
Ions in solution or adsorbed in outer space	Ions presumably in vacuoles

Regarding the active component of ion absorption by roots, wide acceptance of the concept of ion-binding compounds or carriers seems to obtain (Gauch, 1957; Epstein, 1956). The active accumulation of ions appears to involve their combination with protoplasmic constituents, and this is the basis for selectivity.

All carrier theories involve a metabolically produced substance which combines with a free ion. The carrier-ion complex can traverse barriers or membranes not permeable to free ions. Following the transfer across such a barrier, rupture of the ion-carrier complex results in the discharge of the ion into the inner space, perhaps with the restoration of the carrier (Jacobson *et al.*, 1950; Epstein, 1956).

Potassium, rubidium, and cesium compete for the same site, whereas sodium and lithium entry involve other carriers (Epstein and Hagen, 1952). Of the alkaline earth ions, calcium, strontium, and barium compete for identical sites. Magnesium accumulation occurs separately (Epstein and Leggett, 1954). Among the anions, nitrate has a carrier of its own (Van den Honert *et al.*, 1955); selenium but not chloride, nitrate, or phosphate compete with sulfate (Leggett and Epstein, 1956); chloride and bromide compete for the same carrier (Epstein, 1953); HPO_4 and H_2PO_4 enter separately (Hagen and Hopkins, 1955).

The identities of the ion-binding compounds involved in accumulation are not known, but there are many hypotheses. Ordin and Jacobson (1955) propose that ATP may react with Krebs cycle intermediates to form or to destroy ion carriers. Tanada (1956) supposes that the carriers are ribonucleoproteins, with nucleic acid binding the cations and the protein moiety binding the anions. Stewart and Street (1947) suggest that the carriers are phosphorylated nitrogen-containing intermediates in protein synthesis. The carrier is supposed to release bound ions upon incorporation into protein, with release occurring at the site of protein synthesis.

Robertson *et al.* (1955) implicate mitochondria in ion binding and transport, and have found accumulation of both cations and anions in these protoplasmic bodies. Florell (1956, 1957) also has suggested that mitochondria may be ion carriers.

Of course, Lundegardh's massive work has focused attention on the role of the cytochromes in the active transport of ions. His views are summarized in a recent review article (Lundegardh, 1955). Certainly there is close correlation between cytochrome activity and ion uptake, but as pointed out by Becking (1956), this is not proof that anion transport is achieved directly through the operation of the cytochrome system.

Recently much attention has been paid to the passive component of ion absorption by plant roots and other tissues. Interest in this area arose from the observations that an appreciable portion of the volume of plant is accessible for the entry of ions by diffusion or mass flow. Such portions of root volume have been referred to as "apparent free space" (AFS) (Briggs and Robertson, 1957) or as "outer space" (Epstein, 1956).

Briggs and Robertson (1957) regard the free space as, ". . . the intercellular space, wet cell walls and, for many solutes, the cytoplasm surrounding the tonoplast." Mitochondria may be included in the AFS, possibly affording adsorption sites for both cations and anions. The tonoplast is regarded as the barrier separating the inner from the outer space.

Epstein (1955) and Epstein and Leggett (1954) have found the AFS of seedling barley roots to be about 23 per cent of the root volume. Sulfate

ion concentration in the free space was found to be equal to that in the ambient solution, free-space sulfate being freely dialyzable (Epstein, 1955). Cations can exist in the free space either as solute or adsorbed ions, only those in solution dialyzing when roots are transferred to water. Additional amounts are displaced by salt solutions (Epstein and Leggett, 1954). There appear to be more cation than anion adsorption sites in the free space of barley roots (Epstein, 1955).

Briggs and Robertson (1957) discuss the occurrence and the measurement of AFS. They point out the importance of Donnan effects, arising because of the ion exchange character of roots.

There has been considerable interest in the implications of the free-space concept with regard to the translocation of ions to plant tops. According to Epstein (1956), ions actively accumulated by roots not only are not exchangeable, but are not free to move to tops. Apparently those ions which are most readily transported to the tops of plants are those which exist in the outer space. In this regard, Wiebe and Kramer (1954) studied the translocation of sulfate, calcium, strontium, rubidium, and iodide from roots. He found that the greatest transport was from the region of water absorption. Ions accumulated in the apical portions of roots were fixed strongly and were not exported.

Hylmo (1955) and Wright and Barton (1955) found the movement of ions to shoots to be dependent on rates of transpiration and water absorption, indicating that mass flow may be important in the movement of substrate ions to plant leaves. In a later paper, Hylmo (Kylin and Hylmo, 1957) reported that the relative contributions of active and passive processes to ion accumulations in shoots depended both on water absorption and on the concentration of the medium, the passive component being more important at high concentration (5 me per liter) than at low (0.5 me per liter).

The free space concept allows for a mechanism of salt transport through root systems which does not require the export of ions which have been actively absorbed. Hylmo (1955) suggests that cells of plant tops, as well as of roots, may accumulate ions from the transpiration stream. Epstein (1955) came to the same conclusion. Gluekauf (1955) comments that, of the two processes involved in ion uptake by plants, nonequilibrium transport is of greater importance for transpiring parts.

The general significance of mass flow in supplying ions to the cells of plant tops cannot be fully assessed at present. Selectivity is difficult to explain, particularly where the virtual exclusion of ions such as sodium from some plant tops occurs. Any ions which enter roots and are transported upward by mass flow must come into contact with numerous adsorption sites and actively accumulating cells. This will lead to continuous varia-

tion of ion concentrations in the transpiration stream. Perhaps this supports the observation of Kylin and Hylmo (1957) that ions from dilute external solutions do not appear to reach plant tops through passive absorption.

3. *Plant Absorption of Calcium and Magnesium*

Over-all relations between ion concentrations and ratios in nutrient solutions and the ion contents of plants may be obtained from the work of Collander (1941). Apparently, marked competition occurs only between chemically similar ions, such as potassium-rubidium and calcium-strontium. These observations apparently are large-scale manifestations of the effects studied by Epstein (1955) and others. Beckenbach *et al.* (1938) and Beeson *et al.* (1944), in extensive nutrient solution experiments, also found the plant content of a particular ion to be largely accounted for by the concentration of that ion in solution and that competitive effects were less important.

The results of studies of plant nutrition in soils and other ion exchange systems are different. Here competitive or complementary effects are most important (Mehlich, 1946). High levels of potassium or sodium markedly depress the quantities of calcium and magnesium in plants (Mattson, 1948; Mehlich, 1946), whereas calcium and magnesium compete with one another when supplied in adsorbed form (Vlamis, 1949; Elgabaly, 1955; Walker *et al.*, 1955; Milam and Mehlich, 1954).

Apparently the larger competitive effects between dissimilar ions are observed with soil cultures rather than with nutrient solutions because of soil factors which influence the "availabilities" of the ions. Though it is not at all certain just how "availability" can be described in chemical terms, it appears to be related to ion exchange behavior in much the same way as are ion concentrations in soil solutions. Extensive work in this area has been performed by Mehlich and co-workers and has been summarized by Mehlich and Coleman (1952). The general procedure has been to examine ion concentrations in the solution phase of soil-water mixtures after incomplete exchange, brought about by the addition of small quantities of HCl, and to relate these concentrations to the cation contents of plants. Quite accurate predictions of plant composition have been possible in some instances (Milam and Mehlich, 1954).

A fundamental difficulty in approaches of this kind is that it is not known how plant roots mobilize cations from soils. Newton (1923) believed that CO_2 produced by plant roots dissolved in soil water to form carbonic acid, and that this replaced metal cations from exchange spots. Others (Jenny and Overstreet, 1939) have postulated direct exchange between hydrogen ions produced by roots and exchangeable cations sorbed

on soil particles. It also has been suggested from time to time (Mehlich and Drake, 1955) that compounds such as organic acids may be excreted from roots and may solubilize bound ions.

Regardless of the mechanism through which exchangeable cations enter the soil solution and become available for absorption by plant roots, it seems reasonable that there are two general factors which largely control the "availability" of a given ion to plants. One of these is the effective concentration of the ion in the soil solution. The other is the rate at which solution concentration is renewed as ions are removed by plant roots.

Much emphasis has been given to relations among type of soil colloid, percentage base saturation, and ion uptake by plants (Mehlich, 1946; Allaway, 1945; Mehlich and Coleman, 1952). In view of what was said earlier about sources and magnitudes of cation exchange capacity, reexamination of this matter is desirable. Allaway (1945) and Mehlich (1946) both found the percentage of exchangeable calcium replaced on the addition of equivalent amounts of HCl to variously calcium-saturated clays and organic matter samples to be in the order: peat > kaolinite > illite > montmorillonite. Mehlich (1946) observed that 80 per cent calcium-saturation of beidellite gave the same percentage release of calcium as did 35 per cent saturation of kaolinite, or 25 per cent saturation of peat. Mehlich and Colwell (1943) and Allaway (1945) found that plant uptake of calcium from soils or from clay-sand mixtures closely paralleled the release patterns noted above. Eck *et al.* (1957) found that while 75 to 90 per cent calcium saturation (H? complementary) was required to supply adequate amounts of calcium to tomatoes from montmorillonite, 45 per cent was adequate for kaolinite.

Reference to Table I, which lists exchange capacity components for various soils, shows why this should be so. The Cecil soil, containing kaolin clay, has 68 per cent of its permanent charge saturated with bases, but only 23 per cent of its CEC is saturated (pH 8.2). One hundred per cent saturation of permanent charge would result in 33 per cent saturation of CEC. With the Iredell, on the other hand, 100 per cent base saturation of permanent charge corresponds to about 70 per cent saturation of CEC.

Apparently, calcium and magnesium are not readily replaceable from permanent charge exchange spots (Harward and Coleman, 1953; Harward and Mehlich, 1953), but hydrolyze readily from the pH-dependent charges of clays and organic matter. This explains the great increases in "solubility" (Harward and Mehlich, 1953) and "activity" (Marshall, 1950) of calcium at saturation percentages above about 40 for kaolins, 80 for montmorillonoids. Because organic matter has only a weak-acid charge, calcium is released readily by hydrogen ions, even in low pH systems.

The complementary ion effect on the mineral nutrition of plants has

been studied by a number of individuals. Generally, increasing the potassium saturation of soils or other ion exchange substrates lowers the calcium and magnesium contents of plants (Mattson, 1948; Elgabaly, 1955; Mehlich, 1946; Spencer, 1954). Schreiber *et al.* (1957) found that hydrogen (or aluminum), sodium, and magnesium as complementary ions decreased the rate of elongation and the calcium content of radish seedlings. Inhibition of elongation occurred at less than 40 per cent calcium saturation with hydrogen (aluminum) or magnesium as complementary ions, and at about 80 per cent calcium saturation in sodium-calcium systems. Decreased elongation was correlated with removal of calcium from the plant seedlings.

Vlamis (1949) and Walker *et al.* (1955) have established reciprocal effects between the calcium and magnesium nutrition of plants grown in soils or other adsorbent cultures. Walker *et al.* (1955) varied the calcium-saturation of soils from 6.1 to 82 per cent, with magnesium as the complementary ion. He found the calcium content of sunflower plants to vary between 17 and 137 me per 100 g., while the magnesium content varied from 269 (6.1 per cent calcium-saturation) to 68 (82 per cent calcium-saturation) me per 100 g. Around 25 per cent calcium-saturation was required for adequate growth of the plants. Elgabaly (1955), using cation exchange resins as substrates, made similar observations.

Milam and Mehlich (1954) studied the Ca and Mg contents of *Crotelaria striata* grown on several Atlantic Coastal Plain soils with Ca:Mg ratios from 1–24. The results of one experiment may be summarized as follows:

	Ca:Mg				
	1	3	6	9	12
Calcium in plant, me per 100 g.	36	50	55	58	58
Magnesium in plant, me per 100 g.	50	32	25	18	14

Magnesium deficiency was not observed except at very wide Ca:Mg ratios.

One unpublished observation of the authors should be added to this section on complementary ions in the calcium and magnesium nutrition of plants. If one works with cation exchange resins or takes special precautions to obtain and maintain H-clays, so that hydrogen and calcium are the saturating ions, complete base saturation of strong-acid exchange resins and of the permanent charges on soil clays is necessary to obtain survival of the plants. Electrostatically bonded hydrogen as a complementary ion is lethal, apparently through very thorough depletion of calcium and perhaps other ions from seedlings.

All complementary ion effects observed to affect plant nutrition in soils can best be viewed from the point of view of ion exchange equilibria and their effect on soil solution concentrations. Even though plants must somehow "mobilize" adsorbed cations, solid-solution equilibria control the proportions of the various ions which will be made diffusible so that they can enter roots. Thus the effect of large potassium saturations in inhibiting the uptake of calcium and magnesium by plants is a reflection of the exchange equilibria involved. Particularly with dilute soil solutions, most of the "solution sites" (soluble anions) will be pre-empted by potassium (Harward and Coleman, 1953), with deleterious effects on the availability of calcium and magnesium. In extreme cases of unfavorable Ca complementary ion ratio, adsorbent substrates remove calcium from seedling plants. Though objections may be raised to attributing significance to ion ratios in plant nutrition studies, the concept of ion balance in a soil system is quite valid. Ion ratios in themselves have no especial significance, but considered in the light of the exchange capacities and ion saturation of soils, they assume much importance in soil-plant studies.

4. *Plant Characteristics Influencing Absorption of Calcium and Magnesium*

The calcium content of any plant species varies considerably depending on the calcium level of the soil, the ion exchange nature of the soil, and the complementary ions. Pierre and Allaway (1941) compiled the results of numerous plant analyses and obtained the following averages: legume hay, 1.49 per cent; grass hay, 0.42 per cent; cereal fodder, 0.28 per cent. Data of this kind lead to the generalization that some plant species, legumes in particular, have large calcium requirements and also are able to mobilize soil calcium effectively. Certainly legumes, when exposed to a favorable substrate environment, have larger contents of calcium (and magnesium also) than do nonlegumes, and certain plants thrive in soils with low base saturations, while others do not. As discussed earlier, acid soil injury to plants may involve many factors other than calcium supply, and perhaps calcium requirement and ability of plants to mobilize calcium have been overemphasized. Mehlich and Coleman (1952) discussed variations in the calcium contents of various plant species due to substrate nature and concluded that differences within species could be large as compared with inter-species characteristics.

Because exchangeable cations in soils presumably must become diffusible in order to enter plant roots, attention has been given to the production of exchanging electrolyte, usually considered to be carbonic acid, by plant roots. As pointed out by Mehlich and Coleman (1952), the number of equivalents of carbonic acid produced in a soil usually greatly ex-

ceeds the equivalents of metal cations absorbed by a crop. They indicated that a general correlation exists between the amount of CO_2 produced by the roots of a given plant species and the tendency of that species to accumulate metal cations, but doubted that a direct relationship existed. Probably the variations in CO_2 production between species should be regarded as reflecting differences in metabolism. Those metabolic differences probably are responsible for observed cation contents or rates of accumulation.

One view (Mehlich and Drake, 1955) which has received considerable attention recently is that the cation exchange capacities of plant roots are intimately related to ion accumulation. Inter-species differences in ion contents are attributed to the fact that root exchange capacities are not the same.

As in the case of CO_2 production, a general correlation appears to exist between root exchange capacity and the ion uptake characteristics of plants. Legume roots generally have a larger CEC than do roots of grasses, and this is reflected by relatively high calcium contents (Drake *et al.*, 1951). Grasses, on the other hand, contain relatively more potassium than calcium. The case for the importance of root exchange capacity in controlling the mineral nutrition of plants has been presented by Mehlich and Drake (1955).

Root exchange capacities generally have been measured by the titration of electrodialyzed roots with $Ca(OH)_2$. Using this procedure, Drake *et al.* (1951) and McLean *et al.* (1956) have found values between about 12 and 60 me per 100 g. of oven dry roots. These are considerably larger than that calculated from the data of Epstein and Leggett (1954) for the quantity of adsorbed alkaline earth cation in the free space of seedling barley roots ($\approx$ 2 me per 100 g. dry material).

There is some uncertainty as to just what is measured when roots are electrodialyzed and then titrated with a base. As pointed out by Jacobson *et al.* (1950), acid treatment of roots can result in the removal of organic constituents as well as of inorganic ions, though the latter appear to dialyze out more readily. The values for root CEC quoted by Mehlich and Drake (1955) are of the same order of magnitude as the organic acid anion contents of roots (Jacobson, 1955) and may reflect in part neutralization of organic acids produced during electrodialysis.

There are a number of experimental indications that cation exchange capacity may be a more or less incidental characteristic of roots and not connected intimately with ion absorption and transport. Smith and Wallace (1956) found little correlation between the adsorption of calcium and potassium on roots and the calcium content of tops. Epstein and Leggett (1954) found calcium and magnesium to be equally effective in re-

placing strontium adsorbed in the outer space of barley roots, but only calcium interfered competitively with strontium accumulation.

If passive absorption and mass flow are important in the transport of ions to the leaves of plants, the adsorptive characteristics of roots and, in fact, of any plant tissue adjacent to the transpiration stream may modify ion populations in the intercellular fluid and thus may influence the amounts and proportions of ions reaching plant tops. Probably adsorption effects are small as compared with those of active absorption.

The exchange capacity characteristics of roots may be of great importance in the mineral nutrition of crops, but the weight of the available evidence is to the contrary. Future contributions to our understanding of the relation of species characteristics to ion uptake and mineral content will have to be based on more subtle considerations of plant metabolic chains and their influence on gross response.

5. *Plant Responses to Lime*

The soil factor in plant growth and mineral nutrition is a complex one, involving as it does interrelation between ion exchange characteristics, saturating ions, biological activities, and a host of other variables. When an acid soil is limed, many facets of the soil environment are changed. Responses of crops to lime generally have been attributed to changes in the soil environment with regard to: (1) solubilities of toxic substances, aluminum and manganese being those implicated most frequently; (2) availabilities of calcium and magnesium; (3) availabilities of phosphate and potassium; (4) solubilities and availabilities of trace elements; or (5) populations and activities of soil microorganisms.

Perhaps the most controversial aspect of crop response to lime has been that of toxicity of aluminum and manganese versus availability of calcium and magnesium. The difficulty is that the addition of lime to soils simultaneously increases the quantity of calcium (and usually magnesium) in the soil, increases the availabilities of those ions by raising percentage base saturation, and lowers the amounts of exchangeable aluminum and manganese. Aluminum concentration is lowered by precipitation or conversion to nonexchangeable hydroxy-ions and manganese concentration is lowered through precipitation and/or oxidation. In addition, liming increases soil pH, though pH per se generally is not regarded as an important factor, at least in the range usually encountered in soils (Mehlich and Coleman, 1952; Arnon and Johnson, 1942). However, it should be pointed out that the hydrogen ion appears to decrease the active absorption of metal cations by competition for carrier sites (Jacobson *et al.*, 1950; Nielsen and Overstreet, 1955), so that a higher external concentration of a given ion is necessary to support a given rate of absorption at low pH than at high.

Albrecht (Albrecht and Smith, 1953) has been an outstanding and outspoken proponent of the viewpoint that "soil acidity" is nutrient deficiency, particularly of calcium. Mehlich and Colwell (1943) and Mehlich (1942, 1946) appear to agree, at least to the extent that a major result of liming is increased calcium availability.

A number of people who have worked in this field indicate that calcium deficiency is of less importance than is toxicity of aluminum or manganese. Fairly recent work has been done by Schmehl *et al.* (1950, 1952), Fried and Peech (1946), and Vlamis (1953). Ideas concerning aluminum toxicity are based in part on earlier findings that aluminum concentrations in displaced soil solutions, while very small at pH near 6, sometimes are as high as 0.5 p.p.m. in the pH range 5–5.5, and may become very large at more acid reactions (Pierre *et al.*, 1932). McLean and Gilbert (1928) and Ligon and Pierre (1932) have shown culture solution concentrations of aluminum of 2 p.p.m. or less to be toxic to plants, and it appears that levels at least this high exist in many acid soils.

Vlamis (1953) conducted decisive experiments which showed that aluminum toxicity was entirely responsible for the poor growth of barley on an acid soil. In view of the universal occurrence of exchangeable aluminum in acid mineral soils, it seems probable that this will be a general finding. The authors have found that if soil pH is below 5.5 and if the soil contains more than about 1 me of exchangeable aluminum, root growth is largely inhibited.

The concentration of aluminum ions in a soil solution will depend on the amount present, the complementary ions, the water content, and the electrolyte concentration. The general observation (Fried and Peech, 1946; Schmehl *et al.*, 1950) is made that the addition of $CaSO_4$ intensifies rather than helps acid soil difficulties due to aluminum (and perhaps manganese) toxicity, because increasing the salt concentration shifts the exchange equilibrium so that more aluminum ions are in the soil solution. Thus Fried and Peech (1946) found that the addition of 1,000 lb. of $CaSO_4$ per acre increased the aluminum content of the soil solution by 50 per cent, and 4,000 lb. of $CaSO_4$ more than doubled it. Plant yields decreased on the addition of $CaSO_4$ to acid soil (pH 4.8) but not to one limed to pH 6.3. In fact, Jacobs and Jordan (1954) showed $CaSO_4$ to supply calcium to plants more readily than did $CaCO_3$ when soil pH was above 6.

The mechanism of aluminum toxicity is not known. Wright (1937) believes that aluminum interferes with the uptake and translocation of phosphate and that this is the primary cause for aluminum toxicity. In short-term absorption experiments Schmehl *et al.* (1952) observed that nutrient solution aluminum (10 or 100 p.p.m.) interfered badly with calcium accumulation. Ten parts per million aluminum, which is a high con-

centration when compared with levels causing toxicity to many plant species, reduced calcium uptake 9-fold. They suggest the interference with calcium accumulation as a possible mechanism for toxicity. In view of the essentiality of calcium for root growth (Burstrum, 1953) and since a primary symptom of aluminum toxicity is a stunting of the root system, this seems to be an attractive possibility. However, the present authors have studied inhibition of root growth caused by culture solution aluminum, and have found that the effects of aluminum cannot be counteracted by raising the calcium concentration of the substrate.

Anderson and Evans (1956) have found aluminum to inhibit isocitric dehydrogenase and malic enzyme activities in soybean plants, so perhaps we should look to the effects of aluminum on enzyme systems in efforts to explain its deleterious effects.

Manganese toxicity also has been regarded as a primary cause for the poor growth of plants in many acid soils. Quantities of exchangeable manganese and of manganese in displaced soil solutions may be large for soils with low pH (Fried and Peech, 1946; Morris, 1949; Longenecker and Merkle, 1952; Beacher *et al.*, 1952; Heslep, 1951). Mulder and Gerretsen (1952) discussed in detail work relative to manganese toxicity in acid soils and concluded that many soils contain excessive quantities of available manganese.

Even if one takes the view that toxicity of aluminum and/or manganese is responsible for poor plant growth in many acid soils, it is difficult to separate the effects of the two ions. Aluminum generally is present as an exchangeable ion in much larger quantities than is manganese (not commonly present in amounts larger than 1 me per 100 g.). In displaced solutions, however, concentrations of the manganese ion generally are greater, especially on a p.p.m. basis and often in equivalents as well. Presumably this is due largely to differences in the adsorption affinities of the two ions.

Plant species differ in their tolerance to both aluminum and manganese. Undoubtedly this accounts, to some extent, for the responses of different species to soil reaction. McLean and Gilbert (1928) found beets, carrots, and alfalfa to be particularly sensitive to aluminum toxicity, while growth of rye, oats, cabbage, and corn was not markedly reduced by as much as 3.6 p.p.m. aluminum. Black (1957) refers to work which showed 1 to 4 p.p.m. of manganese to reduce the yields of soybeans, lespedeza, and barley, while corn tolerated at least 15 p.p.m. Lohnis (1951) concluded that the tolerance of certain plants to high levels of substrate manganese was related to inefficient absorption. Oats and mangolds, two tolerant species, were found to accumulate considerably less manganese from a given substrate than did susceptible species. On the other hand,

some plants such as tobacco can accumulate large amounts of manganese without apparent injury. Morris and Pierre (1949) found, when lespedeza, soybeans, peanuts, and sweet clover were grown in nutrient solutions containing 2.5 p.p.m. manganese, that the plant contents were 1,402, 529, 378, and 321 p.p.m., respectively. Sweet clover yield was depressed when the plants contained 754 p.p.m. manganese. Yield of soybeans was not depressed to the same extent until contents of some 2000 p.p.m. were reached.

From a consideration of the quantities of exchangeable and soluble aluminum and manganese in many acid soils, it is certain that inhibiting effects on the growth of plants and particularly of roots occur frequently. Probably such toxicities are the most important single factor in acid soil injury to plants.

Availability of calcium and magnesium to plants certainly increases when acid soils are limed. Though a part of this undoubtedly is a pH effect on ion absorption by roots, a most important factor is the relation between the base saturation of clay and organic matter and the "solubility," "activity," or "exchangeability" of calcium and magnesium. These matters have been discussed earlier, with the general conclusion that calcium and magnesium are bound more tightly to permanent charges on soil particles than to various kinds of weakly acidic exchange spots, so that availabilities of these ions should be greater in nearly neutral than in acid soils. However, the ion species complementary to calcium and magnesium in acid mineral soils is strongly bound aluminum, and plants probably can obtain sufficient supplies of calcium from most acid soils.

Melsted (1953) found definite calcium deficiency in corn in certain Illinois soils. Quantities of exchangeable calcium in the soils were relatively low and heavy fertilization had been practiced. Krackenberger and Peterson (1954) have considered the general matter of calcium and magnesium deficiency, concluding that most soils contain sufficient quantities of these ions to support adequate plant growth. They point out that heavy potassium fertilization may add to the soil system a weakly bound counterion which can produce deficiencies of both calcium and magnesium, more frequently the latter.

Many soils of the Atlantic Coastal Plain have low cation exchange capacities and extremely small amounts of exchangeable calcium and magnesium. With these, dolomitic limestone often gives better crop response than does calcitic stone (Milam and Mehlich, 1954; Naftel, 1937), indicating that magnesium deficiency was a primary cause of poor plant growth.

Schmehl *et al.* (1952) have been among those who have studied the effects of limestone and gypsum, singly and in combination, on the growth

and calcium content of plants grown on acid soils. The general finding that $CaSO_4$ accentuates rather than relieves poor plant growth has been interpreted as proving that calcium deficiency was not a factor. This is not necessarily correct, since the addition of any neutral salt to an acid soil displaces aluminum, manganese, and other exchangeable ions, possibly building soil solution concentrations to a point at which toxicity occurs. Calcium and magnesium deficiencies do occur in some soils, though their prevalence probably is not great.

When soils are limed, availabilities of ions such as potassium and phosphate generally are thought to be affected, though there is little agreement as to the magnitude or even the direction of the effect, which usually is not large in any case. Reitemeier (1951) has considered the matter of lime-potassium interactions in great detail, and the reader is referred to his review for an informed discussion.

Generally the availability of soil phosphate to plants appears to increase as soils are limed to the vicinity of neutrality (Black, 1957). This may be due to soil factors, plant factors, or both. In many acid soils the amounts of exchangeable aluminum are very large when compared with the quantities of phosphate added as fertilizer. The implications of this with regard to phosphate fixation and phosphate accumulation by plants are not known, but perhaps are quite important.

Lime additions to soils drastically modify the solubilities of a number of the trace elements, leading to the alleviation of toxicities in some instances, and to the production of deficiencies in others.

Manganese, which can be toxic under some soil conditions, often becomes deficient when acid soils are limed to pH 6.5 or above. Mulder and Gerretsen (1952) have discussed in detail the changes in the oxidation state of manganese which are thought to be largely responsible for its reduced availability when soils are limed. Heintze (1957) has considered both the oxidation of manganese to tri- and tetravalent forms and the complexing of manganese by organic matter as they are related to plant availability. Increasing soil pH, as by liming, favors complex formation as well as oxidation, both reactions leading to reduced availability.

Rich (1956) has surveyed areas of manganese deficiency in the Virginia coastal plain. Using multiple regression analysis, he showed the manganese content of peanuts to be correlated positively with soil levels of manganese, inversely with soil pH and with calcium and magnesium levels.

The solubilities and plant availabilities of copper, zinc, and iron generally are believed to decrease when soils are limed, though iron deficiency for most species of crop plants occurs only in calcareous soils (Brown and Holmes, 1956) or in beach-sand type areas. Gilbert (1952), in reviewing

the role of copper in nutrition, concluded that though copper availability generally decreases on liming, the addition of lime to soils high in organic matter may result in the liberation of bound copper to more available forms. Peech (1941) observed that copper and zinc added to a sandy soil were much less soluble at pH 6 than at pH 3.

Epstein and Stout (1951) found the solubilities of given doses of iron, manganese, and zinc in clay systems to decrease sharply with the addition of $Ca(OH)_2$, though the absorption of the ions by barley roots increased with calcium-saturation up to 75 per cent. Since aluminum was the complementary ion in noncalcium-saturated systems, it is interesting to speculate as to its possible effect on the results of these experiments. Wear (1956) also found the addition of lime to increase the zinc content of sorghum.

The findings of Beckwith (1955), Coleman *et al.* (1956), and Broadbent (1957) concerning the stable complexes formed between soil organic matter and polyvalent metal ions certainly have bearing on the matter of the availabilities of the trace metals from soils. Heintze (1957) has considered this for manganese, and future efforts in this direction will aid in the understanding of factors affecting the supplies of such soil constituents to plants.

Berger (1949) has reviewed soil-plant relations as related to the boron nutrition of plants. Apparently the borate ion is fixed in soils when lime is added. Also, boron requirements of plants apparently are larger under conditions of abundant calcium supply.

Molybdenum occurs in soils as the molybdate ion, which appears to behave chemically much like phosphate. The solubility and availability of molybdate appear to be low in acid soils and to increase considerably on liming (Davies, 1956). In fact, molybdenum deficiency appears to be the first limiting factor for plant growth in many soils.

Anderson (1956) has summarized much of the work done in Australia on lime-molybdenum relationships in legume production, stating the general conclusion: "Lime has profound effects on the response of plants to molybdenum; on some soils responses do not occur if lime has been applied, on other soils responses occur only when some lime has been applied, and on still other soils lime may have little or no effect on the response to molybdenum."

Where lime response is largely due to raising the availability of soil molybdenum, both the yield of legumes and nitrogen fixation by them increases. In many cases, application of nitrogen fertilizers prevents such lime response. With some acid soils (pH less than 5.5) in Australia, molybdenum deficiency is only one of several limiting factors (Anderson, 1956). Addition of lime is necessary for the nodulation of clover, as well

as for increasing the availability of soil molybdenum. Anderson (1956) comments on some acid soils which have molybdenum levels sufficiently low that response to lime alone is not obtained, but supplementary molybdenum must be added as well. Stout and Johnson (1956) and Rubins (1956) have discussed the occurrence of molybdenum deficiency in relation to soils and crops. Rubins (1956) suggests that the United States soils most likely to be deficient are those of the Atlantic and Gulf coasts.

6. *Microbiological Effects of Liming*

Just as higher plants respond to all of the soil factors which interact with lime, so do the microorganisms which inhabit the soil and carry out a multitude of processes which may be favorable or unfavorable to the growth and development of crops.

Apparently the total microbial and fungal population of the soil is little affected by soil reaction in the normal range (Russell, 1950), but the proportions and activities of different groups of organisms are quite dependent on soil reaction, probably for the same general reasons as are crop plants.

Bacteria which carry out nitrification are not very active in soils with pH less than about 5.5 (Russell, 1950). Thus one result of liming acid soils is to increase the rate of oxidation of ammonia to nitrate. This will have the effect of supplying a different source of nitrogen to plants and also may lead to greater leaching losses of nitrogen.

Liming can effect both nonsymbiotic and symbiotic nitrogen fixation. Azotobacter will not fix nitrogen below pH 6 (Black, 1957), though the importance of this in the nitrogen economy of soils is not known. Nitrogen fixation by legumes also is markedly influenced by soil reaction. For example, Mehlich and Colwell (1943) found the nitrogen contents of soybeans to increase regularly with calcium saturation in the case of two mineral soils, but to change little between 40 and 80 per cent saturation (CEC 8.2) for an organic soil. In this connection, there are organic soils in the North Carolina Coastal Plain with pH of 4 and with calcium saturations smaller than 20 per cent on which soybeans grow well and exhibit no growth, nodulation, or nitrogen content response to liming. In mineral soils, however, a relatively high pH, corresponding closely to the saturation of permanent charge with calcium and magnesium, is necessary for nodulation to occur (Pohlman, 1946).

Thompson *et al.* (1954) have considered the effects of soil reaction on various "mineralization" processes which occur in soils. Working with field soils ranging in reaction from pH 5.2 to 8.1, they found that while rate of phosphorus mineralization was correlated with pH, those for nitro-

gen and carbon were not. They suggest that the prevailing view that liming stimulates mineralization reactions may be only partly correct.

The general view that liming leads to the development of more favorable soil physical conditions probably is grounded on two facts. One is that where yield response to lime is obtained, larger amounts of plant residues are returned to the soil. The other is that the production of bacterial polysaccharides and other such materials responsible in large part for soil aggregation is favored in soils of high pH.

C. Lime Factors

1. *Characteristics of Liming Materials*

The commonly used liming materials are calcitic ($CaCO_3$) and dolomitic limestone [$CaMg(CO_3)_2$]. Depending on purity, the neutralizing value of limestones ranges from about 65 to slightly over 100. Pure calcite and dolomite have values of 100 and 109, respectively. Marls consist largely of calcium carbonate, and generally have neutralizing values between 70 and 90.

Calcium oxide or calcium hydroxide is sometimes used as a liming material. Certain by-product slags from smelting operations are also used. The latter are composed largely of calcium silicate, and sometimes contain as much as 10 per cent P_2O_5. Neutralizing values for CaO and $Ca(OH)_2$ are 178 and 135, respectively, while those for slags vary between 60 and 90.

2. *Reaction of Liming Materials with Soil*

The classic view is that lime neutralizes soil acidity through the replacement of exchangeable hydrogen ion by calcium, with the formation of CO_2 and H_2O. It now appears that reaction of lime with the permanent charge component of soil acidity involves the replacement of exchangeable aluminum by calcium, with the formation of $Al(OH)_3$ and CO_2. Perhaps some nonexchangeable hydroxy aluminum ions are formed as well. If more lime than is needed to displace exchangeable aluminum is added, replacement of hydrogen ions bonded to weak-acid spots occurs. This also is the case with H-soil organic matter.

Neutralization of permanent charge in mineral soils corresponds to a pH of near 6. If such soils are limed to higher pH weak acid components of CEC become saturated with calcium and magnesium.

Rates of reaction of liming materials with soils depend largely on the nature and degree of subdivision of the materials and the completeness with which they are mixed. Considerable attention has been paid to rela-

tions between the fineness of ground limestone and its efficiency in neutralizing soil acidity fairly promptly. Many states require that the bulk of the particles pass a 10-mesh screen, with an appreciable part being smaller than about 60–100 mesh.

Typical studies on particle size-reaction rate relations were conducted by Meyer and Volk (1952). They found particles coarser than 20 mesh to have little effect on soil acidity over an 18 month period after incorporation. Particles smaller than 100 mesh reacted rapidly to raise soil pH, while 30–60 mesh materials required from 6 to 18 months to neutralize soil acidity to the extent achieved by 80 mesh and finer particles within one month. Calcitic and dolomitic stones gave much the same results. Meyer and Volk (1952) concluded that, "4–8 mesh limestone has little value as a liming material; that 20–30 mesh material may become effective over extended periods; and that . . . a large portion must be ground sufficiently fine to pass a 40-mesh sieve."

Unpublished data of Mehlich on the rate of reaction of limestone with North Carolina soils showed the rate of increase in pH to vary with the kind of exchange material in the soil, the order being: montmorillonoid > kaolin > organic. Since the reaction of lime with soils depends on fineness, completeness of mixing, and to a smaller extent on soil characteristics, a universal "liming factor" cannot be cited. Usually a factor of 2–3 is considered to be about right (Russell, 1950).

There has been some consideration of the effects of unreacted limestone particles in correcting deleterious effects of soil acidity on plant growth. Meyer and Volk (1952) and Baker and Brady (1954) showed that to be effective in this regard on at least some acid soils, liming materials must react to neutralize soil acidity.

III. Liming Practices

A. Field Responses to Lime

In the humid regions of the United States most of the soils are inherently acid throughout the entire solum. Also in this region are found acid muck and peat soils. In the subhumid regions, many of the surface soils are acid and the subsoils are neutral or alkaline in reaction. In the Chernozem region, acidity is generally not thought to be a problem. However, Kamprath and Olson (1953) found that surface layers of Chernozem soils were acid.

In soils containing two layer minerals and organic colloids, the weakly ionized exchange groups constitute a larger portion of what usually is considered to be cation exchange capacity. In these soils the amount of

calcium in the soil is equally or more important in crop production than is the percentage neutralization of the soil with calcium and magnesium. In contrast, many soils of the subhumid and semiarid regions largely contain 3-layer clay minerals. These soils have a large permanent charge, and, therefore, a large portion of the exchange capacity must be neutralized by calcium and magnesium in order to obtain maximum growth.

Many field experiments with lime have been conducted in past years. In many instances, however, the chemical properties of the soil were not well defined. For this reason apparent discrepancies in responses of crops to liming have occurred. The field experiments conducted by Welch and Nelson (1950) have been taken to illustrate how responses to liming are related to the type of soil colloid and charge developed on the colloid. They studied the calcium and magnesium requirements of soybeans on three soils containing different colloidal materials (Table III). On the

TABLE III

Effect of Calcium Saturation and pH on the Yield of Soybeans[a]

Calcium saturation (per cent)	pH	Yield bushels per acre
	Hyde	
8.4	4.2	15.6
18.8	4.9	27.8
38.0	5.6	29.1
61.0	6.6	29.4
	Bladen	
17.2	4.7	28.5
27.3	5.0	30.8
45.7	5.8	28.0
61.5	6.4	25.9
	Craven	
20.0	4.8	17.4
31.4	5.3	23.3
52.0	6.8	23.1
71.0	7.2	23.3

[a] Data from Welch and Nelson, 1950.

Hyde soil, which contains primarily an organic colloid, an increase in yield was obtained by raising the calcium saturation from 8 per cent to 19 per cent. This raised the pH from 4.2 to 4.9. Further additions of calcium on the Hyde soil resulted in no significant increases in yield. The Bladen soil, which is quite high in organic matter, contains a mixture of organic

colloids and 3-layer clay minerals. No significant increase in yield was obtained with additions of calcium to this soil which had an initial calcium saturation of 17 per cent and a pH of 4.7. On the Craven, which contains 2-layer clay minerals, the yields were increased by raising the calcium saturation from 20 to 31 per cent. This changed the pH from 4.8 to 5.3. Further additions of calcium had little effect on the yield.

The results of these experiments point out that the calcium saturation required for maximum growth of crops in the field is related to the kind of exchange material and source of charge. The charge developed by the Hyde and Bladen soil is primarily pH dependent; therefore, the available calcium content of the soil was more important in determining the yield than was the calcium saturation, and maximum growth was obtained at low saturations. For the Craven soil, a larger proportion of the total charge was pH-independent, and larger base saturation was required.

In determining how much lime is required to raise the pH of the soil, such factors as the texture, organic matter content, and type of clay mineral have to be considered. The effect of these factors can be shown by comparing the change in the pH of two soils which have a similar texture but contain different clay minerals and organic matter contents. Jones and Edwards (1954) found that the addition of 2 tons of lime changed the pH of a Loring silt loam from 5.3 to 6.1. The organic matter content of this soil is quite low and the exchange properties of the soil indicate that the soil contains a considerable amount of 2-layer clay minerals. Fox and Lipps (1955) working on the Crete, a Chernozem soil high in organic matter, and 3-layer clay minerals, found that 4 tons of lime raised the pH from 5.3 to only 5.7. Although these two soils were texturally quite similar, the lime required to move these soils to a given soil pH level was quite different.

Some soils may contain large amounts of calcium in the lower horizons of the soil profile but are quite acid in the surface soil. Fox and Lipps (1955) found on a Thurman soil that liming the soil to raise the pH from 5.2 to 6.3 increased the early yield of alfalfa. However, when the alfalfa roots reached a depth of 3 feet, the plants were able to obtain sufficient calcium and the yields of the no-lime plots were the same as the limed plots. Thus on Chernozem soils which have acid surface horizons, liming will give a better stand and increased growth the first several years.

Many of the early field experiments on liming showed large increases in the yield of corn and small grains. Results of liming experiments at the Ohio Experiment Station (Salter, 1938) show that corn yields increased up to pH 6.8. This increase in yield was primarily due to larger hay growth which added more nitrogen to the soil. Barley was quite sensitive to injury by soil acidity. Below pH 5.7, barley yields were drastically re-

duced. Of the legumes, soybeans were the most tolerant of soil acidity. At pH 5 the yield of soybeans was 80 per cent of that obtained at pH 6.8. Alfalfa and sweet clover were quite susceptible to acid injury. At pH levels of 5.7 yields were approximately half of those obtained at pH 6.8. The conclusion was reached that liming above neutrality was not profitable as the yields were not significantly increased and at higher rates of liming certain trace elements might become unavailable.

The work of McIlvaine and Pohlman (1949) indicates that the yields of corn, small grain, and tobacco were the same in the pH range of 5.5 to 7, as long as adequate amounts of plant nutrients were supplied.

The largest responses to liming have been obtained with legumes. Various studies show that yields of alfalfa, lespedeza, soybeans, and the clovers are increased by liming acid soils (Fox and Lipps, 1955; Jones and Edwards, 1954; Salter, 1938; and Woodhouse, 1956).

Colwell and Brady (1945) reported a good correlation between peanut yields and the percentage calcium saturation of certain soils. Terman and Murphy (1952) investigated the feasibility of growing peas as a supplemental crop in the potato producing areas. The yield of peas was higher on soils with a pH of 5.5 to 5.6 than on soils with a pH of 5.0 to 5.3. As potato scab becomes a problem on neutral soils, it was desirable to keep the soils acid, although peas being a legume would presumably do better on adequately limed soils. Applying 350 lb. per acre of dolomitic limestone with the seed increased the yield of peas at all pH levels without changing the soil reaction of the surface soil very much.

A rather intensive investigation was conducted in Rhode Island by Odland and Knoblauch (1935) on the lime responses of various crops. Such crops as spinach and beets did not grow at a pH level of 4.3, while the growth of cabbage, peppers, and beans was drastically curtailed at this pH level. Such crops as potatoes, tomatoes, and oats gave the same yields at pH 4.3 as at pH 6. In most instances the poor growth was probably due to the toxicity of aluminum and manganese and/or lack of calcium as previously discussed.

The zone of lime placement in the soil has a pronounced effect on the plant response obtained. Woodhouse (1956) showed that more growth was obtained by mixing the lime in the upper 4 inches of soil than by a surface application or by placing the lime at the plow sole depth (Table IV). Most of the root growth of cultivated crops occurs in the upper 12 to 18 inches of the soil profile. Since lime moves very little in the soil profile, the broadcasting of lime on the surface of the soil without thorough incorporation into the soil would be very unsatisfactory. As the function of liming is either to supply calcium and magnesium and/or to alleviate the toxic effects of soluble aluminum and manganese, it is essen-

TABLE IV

Effect of Placement of Limestone on the Yield of Alfalfa[a]

Lime treatment	Yield lb. per acre
None	1025
3000 lb. per acre broadcast on the surface	3382
Mixed in upper four inches	5414
Placed at plow sole depth	4362

[a] Data from Woodhouse, 1956.

tial that the lime be incorporated into the soil zone where root growth will occur.

Uniform incorporation of lime throughout the surface soil is a rather hard task and probably cannot be done in a single operation. For the best results, it is probably best first to apply one half the lime and plow it under and then to apply the rest of the lime and disk it into the soil. This should give a fairly good distribution of lime in the surface soil

B. Tests for Lime Requirements and Liming Recommendations

Soil testing has become an important factor in guiding the use of lime and fertilizer in many states. Fitts and Nelson (1956) have described the status of soil testing in this country, indicating the objectives and the general nature of the procedures used.

The authors, in attempting to obtain a cross section of opinion regarding soil tests for lime requirement, have corresponded with several individuals involved in such programs,[1] and this section is based largely on their contributions, which are gratefully acknowledged.

Measurement of soil pH, usually in a stirred suspension with a water: soil ratio of around 2, is universally practiced. Often this is the only direct measurement on which lime requirement is based. In other laboratories, the change in pH of a buffer solution on the addition of soil gives a measure of exchange acidity and thus of lime requirement. The *p*-nitrophenol-calcium acetate buffer of Woodruff (1947) is used in many cases. In Virginia, a triethanolamine-calcium acetate mixture is used instead. It seems that the use of buffer solutions to estimate lime requirements is regarded as helpful, though factors to convert pH change to tons of lime per acre appear to differ from one soil to another. Larger factors generally appear necessary with heavy soils.

In some states, calcium and magnesium determinations supplement

[1] C. I. Rich, J. Hanway, R. D. Bronson, D. Rouse, D. J. Lathwell, and S. L. Tisdale.

other lime requirement tests. Apparently in the South Atlantic states, where cation exchange capacities and calcium and magnesium levels are low, tests for calcium and magnesium in soils are considered to be helpful. In the Midwest, however, where soil contents of calcium and magnesium are relatively high, this is not considered necessary.

Recommendations for lime additions to soils ideally should be based on the soil buffer capacity between the measured and desired pH. Where this is not measured, an estimate is made from organic matter content, texture, and general knowledge of the character of the soil. One of our correspondents,[1] who declined to "philosophize" concerning lime use in his state, wrote, ". . . in making recommendations for lime (they) are urged to take into consideration such things as the crop to be grown, probability of manganese and boron deficiency, encouragement of disease, accessibility of the area to be limed, steepness of slope, the soil type and its reactions to lime, as well as the soil test."

It is impossible to tabulate specific recommendations, but some general statements are possible. In Indiana, except where manganese deficiency is probable, lime recommendations shoot for a pH of 6.5. Rates as high as 7 tons per acre are suggested, with no recommendations for less than 2 tons. The Iowa laboratory recommends up to 8 tons per acre for very acid soils, with 1.5 tons the minimum amount suggested.

The situation is very different in the Southeast, where rates as small as a 1000 lb. per acre are common (North Carolina) and applications larger than 4 tons are unheard of. In Virginia, quantities range from 800 lb. to from 4 to 6 tons per acre, the attempt being made to reach pH 6.5 except where tobacco, potatoes, or other such crops are to be grown.

Those in charge of lime recommendations also take into account the quality of the limestone to be used, particularly its mesh size. In Iowa, lime rates are based on the assumption that limestone will be 55 per cent effective in the first three years.

There seems to be little choice between calcitic and dolomitic limestones in the Midwest, though dolomitic stone is widely recommended in the Southeast. This is a natural reflection of the differences in capacity and native ion saturation of soils of the two areas.

The occurrence of local areas of acid soils, which produce manganese deficient plants when limed to pH above about 6.2, is a problem in several states. Generally areas in which this occurs are known, and due allowances are made.

It appears to be generally agreed that lime is an ingredient essential to a successful agriculture. It also is agreed that far too little is used. The soil testing programs seem the most effective means for promoting its wider use.

C. Evaluation of Liming Materials

The reactivity of a limestone seems to be related to its active surface area and to its chemical composition. In general, for a given stone the finer the degree of particle size distribution, the more rapid is its rate of dissolution in the soil and hence the more effective it is in changing soil pH. This, of course, is related to an increase in specific surface and thus an increase in sites available for reaction. The relation between particle size distribution and value of an agricultural limestone has been subjected to considerable investigation (Meyer and Volk, 1952) and the fact is established that the finer the material the quicker is its action in correcting soil acidity.

Chemical composition is another factor affecting the reactivity of limestone. Beacher *et al.* (1952) found 60–80 mesh calcitic material to be more effective than corresponding dolomitic material. This difference was not evident for 100 mesh material.

Fundamentally, the most accurate basis for evaluating a liming material is actual field performance. Since this is impractical, various techniques have been derived that attempt to relate certain physical or chemical properties of the stone to reactivity in the soil.

Schollenberger and Salter (1943) developed a chart for the evaluation of limestone based on its "probable activity" which was in turn based on sieve analysis and, to some extent, on chemical composition. This was correlated with the rate of dissolution of the stone in soil systems, measured in terms of the decrease in particle size with reaction in the soil. On this basis, calcite is more effective than dolomite because of its greater rate of dissolution.

A major objection to the sieve analysis technique in general is that it does not take into account any properties of the material that may affect its reactivity other than particle size composition. Thus the intrinsic chemical reactivity, microcrystallinity, and true surface are neglected. Several rapid laboratory techniques have been developed that are based on the rate of reactivity of the liming material with a given reagent (Schollenberger and Whittaker, 1953). Some of the reagents used include carbonated water, sodium acetate solution, ammonium chloride, and acetic acid-sodium acetate mixtures buffered in the soil pH range. In most cases, no correlation has been made with reactivity in the soil, but the methods permit a comparison between materials.

Schollenberger and Whittaker (1953) determined the reactivity of limestone with ammonium chloride by measuring the rate of evolution of ammonia. They found that, in general, the ammonium chloride-limestone reaction varies with the nature of the limestone in the same manner as the

limestone-soil reaction rate. This was taken as an index to the relative activities of different limestones. Their work showed a more rapid rate of reduction of particle size for calcitic limestone than for dolomite. The rate of particle-size dimunition decreased with increasing fineness of the sample. In practice, this would be offset by the greater number of particles per unit weight.

Perhaps the most interesting and potentially promising approach to the problem of limestone evaluation to come forth is that proposed by Love and Whittaker (1954). These workers measured the sorption of krypton by different limestones and calculated the total surface area by the Brunauer, Emmett, and Teller equation for physical adsorption. By this technique, total surface area was found in most cases examined to be enormously greater than the geometrical surface area calculated on the basis of particle size. The relationship between total (BET) surface area and geometrical surface area was not constant for all stones studied but varied from linearity to curvilinearity. This lack of a uniform relationship suggests that grinding limestones to increase surface area for chemical reaction is not equally effective on all materials. Love and Whittaker correlated the ammonium chloride-limestone reaction rates of the materials studied by Schollenberger and Whittaker (1953) with BET surface area and found straight line relationships. Their work also indicated that the total surface was made up of an "interior" surface inaccessible to attacking ions and a "reacting" surface that is proportional to the reactivity of the limestone.

Work thus far conducted on limestone evaluation indicates that no special or simple relationship exists between particle size distribution of a limestone and its effectiveness as a liming material, though in general, as geometrical surface area increases reactivity increases. More work is needed in this area before definite statements can be made regarding the absolute effectiveness of a given limestone. The surface area technique of Love and Whittaker (1954) seems to hold special promise in this regard.

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Author Index

Numbers in italic indicate the pages on which the references are listed.

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I

J

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Subject Index